New York State Utility Transmission and Distribution Investment Working Group

Advanced Technologies Working Group Report

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REPORT SUMMARY

Background

The goal of the Advanced Technologies Working Group (ATWG) is to develop plans for the Utility Transmission and Distribution Investment Working Group to further the goals of the Climate Leadership and Community Protection Act (CLCPA) by considering New York State utilities, transmission owners and operators roles and opportunities for grid investments in advanced technologies. The working group focuses on developing research and development plans for new and/or underutilized technologies and innovations necessary to meet and advance New York's clean energy goals. The context for the ATWG's initial focus are:

I. The transmission system, especially the sub-transmission system (138/115 kV) and below.
II. The 70% renewable energy by 2030 targets.

Objective

To address these goals, the working group is developing plans to study, evaluate, pilot, demonstrate, and deploy new and/or underutilized technologies and innovations that are able to increase electric power throughput, increase electric grid flexibility, increase renewable energy hosting capacities, increase the electric power system efficiencies and reduce overall system costs. Among the questions being considered are the following:

- Are there existing technologies that can improve the efficiency of the grid that are being underutilized?
- Are there research and development opportunities for new or emerging technologies?
- How should we organize the State's research and development effort?
- How do we coordinate work with other State, National, and International research and development stakeholders (EPRI, Universities, National Labs, DOE, ARPAe, etc.)?
- How do we coordinate this work with the other technical analysis and policy working group teams?
- How will utilities integrate new technologies into planning and operations?

Prioritized Issues

The group has prioritized several issues as being key to achieving CLCPA goals. These include the need to:

- Alleviate transmission system bottlenecks to allow for better deliverability of renewable energy though-out the state,
- Unbottle constrained resources to allow more hydro and/or wind imports and the ability to reduce system congestion,
- Optimize utilization of existing transmission capacity and right of ways, and
- Increase circuit load factor through dynamic ratings.

To address transmission system bottlenecks, the group has developed a list of potential technology solutions that could include:

- Utilizing energy storage for transmission and distribution services,
- Investigating low-frequency AC transmission systems,
- Utilizing high voltage DC grids,
- Utilizing and coordinating deployment of flexible AC transmission system components,
- Utilizing dynamic and ambient adjusted transmission line and cable rating systems,
- Utilizing dynamic, closed-loop voltage and reactive power controls,
- Improving operator situational awareness,
- Utilizing wide-area monitoring systems,
- Developing new decision support tools,
- Developing new advanced energy management automation,
- Developing new advanced contingency analysis tools,
- Utilizing dynamic power flow controllers, and
- Developing new renewable energy siting tools.

To address the optimized utilization of existing transmission capacity and rights of way, the group has developed a list of potential technology solutions that could include:

- Transformer, cable, and transmission line monitoring systems,
- Advanced sensor placement tools,
- Advanced transmission and sub-transmission voltage regulation systems,
- Dynamic line and equipment rating systems,
- Energy storage for grid services,
- Advanced high-temperature-low-sag conductors and new composite conductors,
- New compact tower designs,
- Power flow controllers,
- Global information system utilization,
- Sulfur hexafluoride monitoring and alternative systems,
- Modular solid-state transformers and other advanced grid control devices, and
- Improved ability of transmission lines to redirect flow to underutilized lines.

Potential Technology Solutions

The working group engaged the Electric Power Research Institute (EPRI) to develop potential technology solution summaries for the highest prioritized technology categories which included an overview of their technologies, key application considerations, their commercial readiness level, vendor landscape, and field/lab testing experience. The developed summary information, use cases, and/or case studies for these solutions categories included; dynamic line ratings and improved transmission utilization; power flow control devices and distributed or centralized flexible AC transmission systems (FACTS); energy storage for transmission and distribution services; improved operator situational awareness; transformer monitoring; advanced high-temperature, low sag conductors; compact tower designs; and sulfur-hexafluoride or alternative fluid monitoring systems. Below is a brief overview of each of the potential technology solution summaries.

Dynamic line ratings and improved transmission utilization:

There are several factors, including line clearance, thermal rating limits, contingency conditions, that contribute to the overall rating of a transmission line. While other solutions exist for increasing capacity, many efficient solutions have been exhausted or are not feasible. For example, re-tensioning a line can be used to mitigate clearance concerns. However, the conductor, tower, and foundations must all be capable of supporting increased mechanical load for this to be a viable option. Increasing tension can also lead to vibration issues which are detrimental to conductor health if mitigation methods are not deployed. Real time or dynamic rating technologies seek to leverage the time -varying changes in the environment. Utilities using static ratings have more capacity available most of the time due to the conservative nature of the rating method. A static rating is simplest for design and operations as it never changes. The rating today is the same as the rating tomorrow. The odds of the true capacity of the line being lower than a static rating defines the rating risk. Ratings risk tolerance varies by utility and can vary within a utility transmission system. Case studies and available literature show that most utilities would have additional capacity available between 80 and 99% of the time. The amount of extra capacity depends on the real time weather conditions and is examined in the technology summary.

Power flow control devices – distributed and centralized FACTS:

Power flow control devices, in addition to traditional transmission technologies, provide a suite of alternatives to more efficiently direct the flow of power on the grid, improving flexibility and enabling the grid to be more responsive and resilient. Traditional technology solutions to control power flow—such as phase-shifting transformers (PSTs)—have been used extensively for reducing loop flows or to maintain scheduled power flow on certain paths. They have also been used in some cases to reduce overloads by diverting power flow from heavily loaded lines to other lines with spare capacity, increasing the utilization of existing transmission assets and consequently reducing the need for certain transmission upgrades. In recent years, new power flow control technologies have been developed. Relative to the more traditional power flow technologies such as PSTs, flexible AC transmission systems (FACTS), and high voltage direct current (HVDC) technologies, the new PFC devices are simpler, more compact, and scalable. Some of these new PFCs have great potential but still are at an intermediate stage of development, while others are already commercially available, such as the distributed series compensator technology, developed and commercialized by vendors.

Energy storage for T&D services:

Energy storage is increasingly being considered for many transmission and distribution (T&D) grid applications to potentially enhance system reliability, support grid flexibility, defer capital projects, and ease the integration of variable renewable generation. Central to the state's policies and mandates is the need to enhance power system flexibility to effectively manage renewable energy deployment and the associated increase in variability. As power systems begin to integrate higher penetrations of variable, renewable, inverter-based generation in place of conventional fossil-fuel fired synchronous generation, grid-scale energy storage could become an increasingly important device that can help maintain the load-generation balance of the system and provide the flexibility needed on the T&D system. Pumped hydro storage (PHS) and compressed air energy storage (CAES) are long-established bulk energy storage technologies. Utility-scale lithium ion battery storage has expanded dramatically, as decreasing lithium ion battery costs make this an increasingly cost-effective solution to meet T&D non-wire, reliability, and ancillary service needs. Redox flow batteries, sodium sulfur batteries, thermal energy storage (both latent and sensible heat), and adiabatic compressed air energy storage are all in various stages of demonstration. This information provides a concise overview of a wide variety of existing and emerging energy storage technologies being considered for T&D systems. It describes the main technical characteristics, application considerations, readiness of the technology, and vendor landscape. It also discusses implementation and performance of different energy storage technologies. In this report, energy storage systems greater than 10 MW and four or more hours of duration, are considered as bulk and transmission and sub-transmission-connected energy storage.

Improved operator situational awareness:

Recent changes and trends in electrical energy—both on the generation side, with increasing levels of electricity generation from renewable energy sources such as wind and solar, and on the energy consumption side, with new and more efficient consumption technologies—are changing use patterns and dynamical characteristics of the entire infrastructure. Traditional situational awareness tools available to system operators in the energy management system (EMS) will not be adequate due to a stochastic environment with faster dynamics resulting from these changes. Developing advanced analytical tools to perform system security analysis and based on that provide integrated decision support solutions using cognitive systems engineering to the system operators will be necessary. This section discusses some of the advanced situational awareness tools in various stages of technology readiness being developed to meet the future needs. Some of the tools discussed are those using synchro-phasor technology, dynamic security analysis, need for advanced short-term forecasting tools for much granular real and reactive power load as well as solar and wind generation, much faster simulation and analytical tools. In addition, a comprehensive monitoring system to ensure to the operators that all the advanced situational awareness tools are functioning as planned.

Transformer monitoring:

Large substation transformers that interconnect different voltage levels of the grid are major capital assets that are essential to the reliable delivery of economic power. Transformers can also perform a critical role in supporting utility efforts to increase power flows through existing transmission corridors to optimize grid utilization. Given the importance of transformers in a power system—and their high cost and long lead time for replacement—managing transformer fleets to maintain high levels of health and performance presents ongoing challenges for utilities striving to employ their assets to the fullest extent possible while maintaining system reliability and controlling costs. The challenges are compounded by transformer demographics. A high percentage of installed transformers are approaching or have exceeded their forty year design lives. Replacing large numbers of these aging assets is neither practical nor financially feasible, so utilities seek to get as much performance and remaining life as possible from their transformer fleets. System abnormalities, loading, switching, and ambient conditions normally contribute to transformer accelerated aging and sudden failure. Therefore, central to transformer management is effective monitoring to gain a comprehensive view of transformer health, which can help utilities assess equipment condition, diagnose incipient degradation, anticipate problems, prevent failures and extend transformer life. Provided results are properly interpreted, monitoring offers intelligence to support repair/refurbish/ replace decisions that maximize performance and minimize costs. In short, monitoring can help utilities ensure that transformers stay healthy and perform critical functions such as supporting sustained additional loads, and not be the weak links in the power delivery chain.

Advanced high-temperature, low sag (HTLS) conductors:

More than 80% of bare stranded overhead conductors used in transmission lines consist of a combination of 1350-H19 (nearly pure aluminum, 1350, drawn to the highest temper possible—H19) wires, stranded in one or more helical layers around a core consisting of one or more steel strands. The steel strands are coated by one of several different methods to resist corrosion. By varying the size of the steel core while keeping the cross-sectional area of aluminum constant, the composite tensile strength of aluminum cable steel reinforced (ACSR) conductors can be varied over a range of 3 to 1. The mechanical and electrical properties of ACSR (and all aluminum conductors, such as AAC, AAAC, and ACAR) are quite stable with time, as long as the temperature of the aluminum strands remains less than 100°C. Above 100°C, the work-hardened aluminum strands lose tensile strength with time at an increasing rate with temperature. The steel core strands, however, are unaffected by operation at temperatures up to at least 300°C (although conventional "hot-dip" galvanizing may be damaged by prolonged exposure to temperatures above 200°C). The sag-temperature behavior of ACSR is also dependent on the size of the steel core. At moderate to low conductor temperatures, the thermal elongation rate of ACSR is between that of steel (11.5 micro strain per °C) and that of aluminum (23 micro strain per °C). For example, with Drake ACSR, the thermal elongation is 18.9 micro strain per °C up to a temperature about 70°C, but decreases to the thermal elongation rate of the steel core alone (11.5 micro strain per °C) at higher temperatures. Hight Temperature Low Sag (HTLS) conductors are able to operate continuously at temperatures above 100°C (the HT part) without any reduction in breaking strength. In addition, they exhibit thermal elongation rates that are less than ACSR (the LS part). This characteristic allows the HTLS conductor to sag less than a conventional ACSR conductor at any temperature, especially elevated temperatures.

Compact tower designs:

Increasing transmission transfer capacity within existing right of ways is a potentially efficient and economic approach to solving thermal constraints. A compact transmission line may, be defined as a line where the lateral dimensions of the line - tower height, tower width, and minimum right-of-way width - are reduced relative to older existing lines of the same voltage class. There are numerous compact tower designs for horizontal, vertical, and phase compaction that can be considered to increase transfer capacity. The technology summary examines each of the line compaction designs and explores the associated advantages and disadvantages.

SF6 monitoring/ SF6 alternatives:

Electric utilities are facing increasing regulatory pressure and technical challenges related to the management of sulfur hexafluoride (SF6), which is widely used as an arc-quenching medium and as electrical insulation in gas-insulated substations (GIS) and gas-insulated lines (GIL). SF6 is a powerful greenhouse gas and at times can produce toxic decomposition products under certain fault conditions. Several countries outside of the United States and some U.S. states have implemented or are considering regulations to limit SF6 emissions above certain thresholds. In addition, alternatives to SF6 have emerged. The twin challenges of increasing regulatory scrutiny and the existence of potential SF6 replacements put the industry on the brink of significant technological disruption in this area. The issues associated with SF6 management and emerging SF6 alternatives are of concern especially for utilities seeking to build new substations and lines to alleviate transmission bottlenecks, reduce congestion and allow delivery of power from renewable sources from remote or distant locations. Gas-insulated substations and lines offer many benefits including compact size, modularity, physical security and protection from pollution and harsh environments. Their compactness and modularity make them especially suitable when new substations are needed in areas where land space is limited and/or expensive, or in communities that desire visually unobtrusive power infrastructure. The industry thus has two high priority needs regarding GIS/GIL and SF6: effective monitoring and diagnostic technologies to support SF6 management, and answers to significant questions about the dielectric performance, safe and effective handling, operation, maintenance, and disposal of SF6 alternatives. Also needed is a clear understanding of the tradeoffs and expectations utilities may experience when using the new technologies.

Forum / Evaluation Plan

As part of this section, the working group is providing some high-level recommendations for better planning the investment in and implementation of new technologies for the New York state electricity grid. The following three items are of great value in the evaluation and coordinated implementation process:

Operation of a Joint Utility R&D Advisory Working Group:

As transmission and distribution grids are evolving, it is becoming increasingly evident that the grid operates in an integrated manner. In an environment like NY, where a highly interconnected electricity grid is owned by several transmission owners, proper coordination among all these stakeholders is needed to optimize the grid operation and performance. This also applies to the deployment of advanced technologies, especially the ones that are utilized for improving the power system operation and control. Many of these technologies only provide their true value and maximum potential if deployed strategically in a coordinated way. For New York to be able to more effectively utilize and adopt new technologies, it is, therefore, of high importance to maintain proper coordination among all relevant stakeholders on this topic. This will allow new ideas to be thoroughly discussed and evaluated from a holistic perspective, identifying the best use cases for them, which can provide maximum value to the grid overall. It will also allow for pilot or demonstration projects as well as the coordinated optimal deployment when a technology reaches a potential implementation stage.

A second significant benefit of an ongoing advisory working group is the continuous exchange of information between transmission owners and other stakeholders in a more comprehensive and formalized way. This will lead to sharing experiences with specific technologies or products, therefore avoiding duplication of effort leading to similar learnings or mistakes. Coordination would also avoid duplication of research resources and funds. When it comes to new technologies and ideas, it is important and valuable to have some initial joint R&D efforts until a technology is brought to a fairly mature level and could then be adopted up by entities who are more interested in it or get the most value out of it for actual implementation and deployment. Such an advisory group could coordinate such initial research and development stages.

Consequently, this collaborative process will result in improved prioritization of R&D work, better focus on technologies that provide value to the overall grid, and therefore, overall a more streamlined and optimized decision and investment making process in NY's roadmap for adopting and utilizing new technologies for successfully achieving its CLCPA goals.

Creation of a Research and Development Venue:

In many cases, appropriate evaluation of new technologies cannot be performed only by literature surveys, shared experiences, or developer/vendor information. Specific grid details or requirements might make it difficult or inaccurate to extrapolate performance and benefits based on experience from others. In such cases, further specific studies or demonstrations are needed to appropriately evaluate a technology and obtain more confidence in it. Given that actual field demonstrations are often complex and risky, realistic studies, tests, and demonstrations taking place in a controlled laboratory environment provide a very good alternative to experiment with and further develop new technologies. This approach has been successfully used in many other places worldwide, such as in Europe (e.g. https://www.hvdccentre.com/) Asia (e.g. https://www.kepri.re.kr:20808/newEng/index, http://eng.csg.cn/Press_release/News_2019/201909/t20190916_303623.html), and Canada (e.g. http://www.hydroquebec.com/innovation/en/institut-recherche.html, http://energymanitoba.com/partners-members/manitoba-hvdc-research-centre/). Such a laboratory environment should have several key features and provide key capabilities that would allow stakeholders to properly experiment, study, test, and evaluate new ideas and technologies in an accurate and realistic way and also allow them to gain experience working with them and operating them prior to field deployments. Some crucial capabilities include, at a high-level:

- The venue should provide a collaborative environment where utility personnel can work with various other stakeholders as well as technology providers.
- The venue should have research, development, and testing capabilities spanning a wide area of technologies that relate to the electricity grid operation at all levels (transmission, sub transmission, distribution).
- The venue should provide a large variety of analytical and physical tools that would allow people to run studies and experiment with software or hardware equipment and new apparatus or techniques.
- The venue should provide a variety of modeling and simulation tools and capabilities that would facilitate studies and experimentation. Such tools should be using actual grid models and data that can mimic the reality as much as possible. In order for such an environment to be useful and successful such models should be kept up to date and provide a high-fidelity representation of the grid at various levels and domains to support a variety of different studies.
- The venue should have the capabilities, policies, and processes in place to appropriately secure confidential data and ensure proper utilization of such data accordioning to utility and governmental policies and guidelines.
- The venue should have enough space and other capabilities to accommodate demonstration and testing of larger-scale hardware equipment. Such a lab should go beyond performing traditional model based studies and should be able to provide capabilities to test software and equipment in set ups as close as possible to real field conditions, providing capabilities for new system configuration, preliminary commissioning testing prior to moving to the field commissioning, as well as training for personnel on the actual equipment in a safe lab-based

training environment. The venue should be able to support such equipment configuration, commissioning, and training needs for new technologies.

- The venue should be able to serve as a "one-stop shopping" location, where new technology developers and vendors can reach out to the entire group of NY electricity grid stakeholders and present their ideas for a more collaborative and coordinated discussion and evaluation.

Development of such an environment would allow NY stakeholders to work more closely together and seek collaborative solutions to common issues, avoiding duplication of investment and effort, in particular at earlier R&D stages. It would also provide NY utilities a controlled environment that they can experiment and test (or even to some extent develop and expand) new technologies without having to solely rely on vendor or other third-party information and experience. Such an environment could also be leveraged by manufacturers or renewable energy developers for some of their more detailed and advanced studies, potentially resulting in reduced project development costs.

Coordinated technology evaluation plans:

Based on the above two items, a coordinated pilot implementation plan can be devised for a potentially useful new technology. The plan would approximately follow the high-level process presented below:

- A new idea or a new technology is proposed as a solution for addressing one or more specific issues on the NY grid resulting for CLCPA goals.
- The idea is presented and discussed in the joint utility advisory working group.
- Utilities discuss any knowledge or experience that they may have with this technology and potentially seek input and information from vendors or other entities or utilities outside NY.
- If the idea is deemed of interest and value by some of the NY utilities and is seen as having good potential for benefiting the NY grid, a study or a lab testing and demonstration project is defined to further evaluate the technology in a more systematic way and its applicability and benefit for the NY grid.
- Based on the lab evaluation, if the idea is determined as viable for moving forward, a preliminary plan for pilot implementation(s) is created and a cost/benefit analysis is performed. Lab testing can be used to assist, facilitate, and de-risk the specific pilot implementation.
- Based on the pilot outcomes, the idea/technology is picked up by the entity or entities that are more appropriate for implementation and large-scale deployments, either based on the fact/estimation that they get the most value of this technology, or based on the fact/estimation that implementation in their system(s) would provide the most benefit for the grid. At this stage deployment of this technology becomes a regular utility project that follows all the existing or updated implementation policies and procedures.

Benefit and Cost Analysis

The group has gathered information for the cost and benefit analysis of potential technology solutions; and provided some recommendations.

A Benefit and Cost Analysis (BCA) of any Research & Development (R&D) project should consider both quantitative and qualitative factors to make a base case for the investment. It should also compare similar projects to determine the potential benefits, risks, and likelihood of success. A BCA should be conducted before allocating funds to any project. A thorough analysis of a project should identify all potential benefits and the probability of achieving goals, compared with the all-in associated costs. The outcome of the analysis should help decision makers determine if the project is feasible and if it should proceed, or if the funds are better spent elsewhere. If a project is to go ahead, the benefits should be compared to the costs and meet the intended goals. A thorough BCA should identify the purpose and goals behind the project, gather business and project requirements, identify all of the resources to be used, determine the metrics to measure success, and consider other potential options.

The Utilities have developed a BCA Analysis Handbook that provides a framework based on the February 26, 2015 Order Adopting Regulatory Policy Framework and Implementation Plan. The BCA determination recognizes that the Reforming the Energy Vision (REV) is a long term, far reaching initiative that will eventually touch most parts of the Utilities' infrastructure and business practices. The BCA framework recognizes that a quantified analysis on the wide-ranging set of potential benefits in a REV approach against hypothetical future cost scenarios under both REV and conventional approaches would be artificial and counterproductive. Such an effort would distract from the far more important task of carefully phasing the implementation of REV so that actual expenditures are considered in light of potential benefits recognizing that in this multi-phased implementation process, benefits and costs will be considered with increasing specificity. The Utilities have prepared a BCA Handbook to provide a foundational methodology along with valuation assumptions to support a variety of utility programs and projects. The BCA Handbook was issued with the expectation that it will be revised and refined over time and as informed by new opportunities that REV provides, experience gained from programs and project deployment, and experience gained from transmission and distribution grid system enhancements. The Handbook typically covers the following four categories of utility expenditures, as required per the BCA Order: investments in distributed system platform (DSP) capabilities; procurement of distributed energy resources (DER) through competitive selection; procurement of DER through tariffs; and energy efficiency programs. The Handbook was prepared consistent with the BCA Order list of principles of the BCA Framework. These principles stated that the BCA Handbook should establish the BCA Framework, be based on transparent assumptions and methodologies, list all benefits and costs including those that are localized and more granular, avoid combining or conflating different benefits and costs, assess portfolios rather than individual measures or investments (allowing for consideration of potential synergies and economies among measures), address the full lifetime of the investment while reflecting sensitivities on key assumptions, and compare benefits and costs to traditional alternatives instead of valuing them in isolation. Given these principles and framework guidance, the purpose of the BCA Handbook is to provide the methodology for calculating benefits and costs of their programs, projects and investments using the input assumptions as provided within and/or referenced to external sources. The Transmission Policy Working Group has developed recommended changes by including CLCPA benefits in the scope of the Transmission Planning criteria. This effort will allow the development of transmission upgrades that may not be justifiable under the current transmission criteria which focus more on system reliability. This approach can be applied to the full range of potential local transmission and distribution projects that have the potential to unlock CLCPA benefits. The methodology is focused on additional CLCPA-related metrics, and uses a simple, easily repeatable methodology that would include a combination of metrics enhances and understanding of project contributions to CLCPA. These objectives would include a BCA to establish relative cost-effectiveness, net benefits to capture the scale of benefit achieved, and incremental cost of additional hosting capacity to evaluate distribution projects. Key preliminary recommendations being considered are, the commission accepting the proposed transmission related BCA guidelines for CLCPA projects, and the simple, consistent, repeatable BCA guidelines to allow a transmission owner to efficiently prioritize its CLCPA-related investments.

The Department of Energy (DOE) developed guidance for evaluators who conduct impact assessments to determine the economic benefits and costs, energy benefits, environmental benefits, and other impacts of the Office of Energy Efficiency and Renewable Energy's (EERE) R&D projects. The impact assessments covered in their guide are intended to address the following questions of interest to managers of DOE, Congress, the general public, and other stakeholders: To what extent has the project produced energy and economic benefits relative to the next best alternative? To what extent has the project achieved environmental benefits, and enhanced societal benefits? To what extent has the project cultivated a knowledgebase in the research community that has impacted innovations in today's markets? Would today's commercialized technologies likely have happened at the same time, and with the same scope and scale, without the project efforts? Was the public investment worth it? In addition to energy and economic impacts, the approach should quantify emissions reduction, environmental and other health benefits, health cost avoidance, energy policy benefits, and knowledge creation and diffusion. It addresses attribution of benefits through the use of the counterfactual model which seeks to compare outcomes with what would likely have happened in the absence of the R&D project. The method presented in this guide builds on the R&D impact assessment approach used by the National Institute of Standards and Technology (NIST) and improves on the approach employed by the National Research Council (NRC).

A study completed by several European agencies that explored the BCA of R&D projects found that the use of BCA to evaluate these types of projects have often been hindered by the intangible nature and the uncertainty associated to the achievement of R&D results. The core of their BCA is an evaluation of the project socio-economic benefits and costs. The net effect on society is computed by a quantitative performance indicator (the net present value, or the internal rate of return, or a benefit/cost ratio). In line with the general BCA fundamentals, a BCA model of these type of projects should make use of; shadow prices to capture social costs and benefits beyond the market or other observable values; a counterfactual scenario to ensure that all costs and benefits are estimated in incremental terms relative to a 'without project' world; discounting to convert any past and future value in their present equivalent; and a consistent framework to identify social benefits by looking at the different categories of agents (producers, consumers, tax payers, rate payers). The project evaluations are dividing social benefits in two broad classes. The first is benefits accruing to different categories of direct and indirect users of the infrastructure services, such as firms benefitting from technological spillovers, consumers benefitting from innovative services and products, and the general public. The second is the identification of use-beneficiaries that is project specific reflecting the social value of the discovery potential of the research project.

It would be the goal of the ATWG to coordinated and evaluate all BCA options for each R&D project pursued in this effort and continue to improve on these BCA methods as new and underutilized technologies are being evaluated in New York State.

Impediments / Mitigations

The figure below summarizes key issues that utilities consider as the factors that could delay or prevent the implementation of new technology solutions in the three highest prioritized technology categories. Generally, while these technologies may have demonstrated their technical capabilities to facilitate the CLCPA, these issues could introduce some uncertainties or make it difficult to benchmark these new technologies against the conventional solutions.

Technology Solution	Impediment	Mitigation
Dynamic Line Ratings (DLR) and improved overhead and underground cable transmission utilization	Effectiveness: It is difficult to ensure the higher ratings can always be achieved when they are needed in the future. Particularly, if the ratings are depending upon critical factors such as the wind speed that has high variability. This could make it difficult to compare the benefits of DLR against the conventional solutions	Additional studies should be conducted to better determine the future benefits from DLR and the extent that DLR could be effectively utilized in the local and bulk transmission system
Power flow control devices – distributed and centralized	Coordination: Power flow control devices don't increase system capability but redirect power. Increasing the utilization of this technology may create planning operational complexity since it could impact wider areas.	A comprehensive study should be conducted to evaluate potential impacts from large-scale power flow control utilization and the systems needed to ensure that the operations of these devices will be well coordinated.
Energy storage for T&D services	Cost Estimate: Sufficient cost estimate for a storage project is needed to allow it to be compared against conventional solutions. Currently, it is difficult to come up with this level of estimate.	A guidance document and compilation of project experience should be developed to help facilitate cost estimations
	Specifications: Detailed specifications of Storage require more information that may not be available at this point. For example, future congestion pattern is needed to develop the specifications of the Storage	Additional studies at amore granular level should be conducted to provide relevant information regarding future benefits.
	Benefit quantifications: The true benefits or use cases for Storage are still unclear. This can put Storage in disadvantage positions when benchmarking it with conventional solutions.	Similar to the above, additional studies should be conducted to understand benefits and impacts of various use cases. A guideline to quantify the benefit could be useful as well

Conclusions / Recommendations

In summary, the group concludes the following:

1. The group has prioritized several issues and potential technology solutions as being key to achieving CLCPA goals. These technology solutions are consistent with the transmission needs identified by the Technical Analysis working group.

2. A survey of the group found that various members are already implementing either operationally or in R&D pilots some of the technology solutions identified and reviewed in this study. For those technology solutions already being implemented by some, there is

opportunity for knowledge transfer among the members of the group. Through knowledge transfer, members can learn from each other so as, to be in better position to assess further adoption of the technology solutions. The table below provides an overview of the implementation of these technology solutions among the group members.

Technology Solution	Avangrid	Central Hudson	Consolidated Edison	LIPA/PSEG LI	National Grid	Orange and Rockland	NYPA
Dynamic line ratings and improved transmission utilization	Ongoing Pilot (NYSERDA Future Grid Challenge)	Past R&D pilot with mixed results	Use on underground transmission lines	Limited use on underground transmission lines	Demonstrated in New England; currently deploying Line Vision technology in Upstate NY	Limited success with past installations, waiting for technology to mature	R&D pilots only with various technologies
Power flow control devices – distributed and centralized	Several PARs used in Rochester; proposed Smart wire technology as alternative for ongoing Utility Study	Pilot temporary Smart wires project on 115kV, proposed permanent project on 345kV (in NYISO gold book)	Use of PARs at transmission level	Limited use of PARs at transmission level	Demonstrated Smart Wires technology in New England	-	Planning for potential pilot
Energy storage for T&D services	NWA solicitation for any new transmission project; A few storage installed; Proposed several storage for ongoing Utility Study	In design battery storage project per PSC order	Limited installations of utility owned energy storage	Limited installations of BESS on distribution system with PPA. Potential developer owned BESS on both T&D system	Limited installations of utility owned energy storage	Actively working with developers as well as planning on installing battery storage along with the construction of new distribution substations	One pilot at transmission level but mainly as generation asset
Improved operator situational awareness	ongoing improvement on alarms	Various technologies in use, in investigation phase	Efforts have been on improving the managing of alarm information	-	proposed	Improving alarm information by getting discrete alarms	Mainly work phasor measurement units
Transformer monitoring	Various types of monitoring in use throughout system	Various types of monitoring in use throughout system	Various types of monitoring currently in use throughout the system	Various types of monitoring currently in use throughout the system	Various types of monitoring in use throughout system	In operational use for predictive maintenance and asset management	In operational use for predictive maintenance and asset management
Advanced high-temperature, low sag (HTLS)	Proposed at one location for CapEx project; will be considered in the future	-	-	Use of ACSS on OH transmission lines	Demonstrated in New England	Use of ACSS on a number of transmission projects in past with success; only installed steel core conductors, with both conventional (round) and trapezoidal stranding	-
Compact tower designs	-	-	-	-	-	-	-
SF6 monitoring/SF6 alternatives	SF6 monitoring system are used in the current/planned facilities	69kV vacuum breaker installed in one location	SF6 monitoring in use to help identify leaks for repairs	Utilization of 69kV vacuum breakers currently under review	SF6 monitoring in use to help identify leaks for repairs, currently discussing low voltage vacuum breaker pilot	-	-

3. It would be beneficial for the joint utilities to share R&D knowledge on a regular basis. This helps to increase awareness of state-of-the-art and emerging technologies among the joint utilities, thereby creating greater interest to assess the technologies and possibly leading to their use.

4. In furthering the goals of the CLCPA, it would be more cost-effective for the joint utilities to work together than separately to test out and assess the use of new technologies. However, there are issues that need to be addressed before this can happen. Foremost among the issues is the need for funding, which NYSERDA can help cover most, if not, all the funding requirements. Another issue is the need for a governance structure to select, among many things, which joint R&D projects will be funded.

5. The challenges of adopting advanced technologies include the following:

   - Advanced technologies typically include an inherent risk of not meeting expectations or even failure. Therefore, their results and effectiveness are not guaranteed until thoroughly tested and evaluated and until enough field operating experience is obtained.

   - Advanced technologies are not typically a substitute to more traditional solutions or system upgrades, but they can be used to supplement such solutions and ensure that additional value is extracted from such solutions in longer timeframes.

   - Advanced technologies may need close coordination between stakeholders in order to result in implementations that are effective and provide value. In many cases, unless deployed in a wider scale and in a coordinated way, benefits might not be demonstrated by a few individual pilot installations.

   - Advanced technology solutions might typically require upfront effort and funding for testing and pilot projects, which by themselves do not demonstrate benefits. These efforts are needed, however, in order to make the technology more mature, obtain operational experience, and move the technology to a stage that it can be reliably deployed and start demonstrating benefits. This implies that many new technologies might not have a valid "business case" as there are upfront sunk costs and the benefits may have to be over longer-term to substantially surpass the upfront costs. In addition, many benefits may not be easily quantifiable and may need additional actions and assumptions to occur prior to being materialized.

   - Advanced technologies are not equally suited throughout the system and the State. The regional and local environment and existing transmission configurations will have to be considered as to where would be appropriate to incorporate the various advanced technologies.

6. Any joint R&D projects should initially focus on these three technology solutions: dynamic line ratings, power flow control devices, and energy storage for T&D services, because although additional capacity would be needed on the transmission network, these

technologies could enhance operator flexibility to ensure reliability and reduce system congestion furthering the goals of CLCPA in integrating greater amounts of renewables.

7. The above three chosen technology focus areas are not a direct replacement for additional system capacity. When system upgrades are needed to mitigate the challenges of the future, Transmission Operators are encouraged to utilize new technologies such as HTLS and innovative tower design in project design when such technologies are more cost effective than traditional ones.

8. New York State has a wealth of R&D resources such as NYPA's small-scale Advanced Grid Innovation Laboratory for Energy (AGILe), academic institutions and a national laboratory that should be utilized to help the joint utilities to further the goals of the CLCPA prior to the development of new resources.

9. The intangible nature and the uncertainty associated with the achievement of R&D results often hinder the BCA of R&D projects. More specifically the risk resides primarily with the anticipated benefits in the BCA calculation, because the benefits are dependent on the success of the R&D project. Therefore, the anticipated benefits in the BCA calculation should be risk adjusted based on the project's likelihood of success. This will help guide the selection of projects with greater likelihood of success while not precluding projects with potentially home run benefits.

Based on these conclusions, the group believes there is an opportunity to create a New York State focused R&D consortium to be comprised of, at minimum, the New York State investor owned utilities ("IOUs"), NYPA, LIPA, the NYISO and NYSERDA to expedite the assessment and adoption of state-of-the-art and advanced technologies that are already being used elsewhere in the U.S. or the world. This R&D consortium would also help each IOU to identify and assess which of the state-of-the-art technologies it should implement or expand their use, consistent with how best to further the goals of the CLCPA while also addressing the need to provide affordable, safe and reliable service to its customers.

Therefore, the group recommends the following:

1. A New York R&D consortium should be created with the initial task to identify two to three R&D projects, preferably one project for each of the three technology solutions: dynamic line ratings, power flow control devices, and energy storage for T&D services. These initial projects should demonstrate the use and benefits of the selected technologies. The selected technologies should be state-of-the-art and commercially available.

2. The R&D consortium will initially include all the New York State IOUs, NYPA, LIPA, the NYISO and NYSERDA and may be expanded over time to include academic institutions in New York State as well as possibly Brookhaven National Laboratory on Long Island.

3. The projects proposed should be evaluated based on the potential benefits and costs of the project but should also be risk adjusted based on the project's likelihood of success.

4. Projects selected by the R&D consortium should be funded through NYSERDA, with the IOUs, NYPA and LIPA participating in the project having the opportunity to choose to support the project through co-funding or in-kind contribution on a project by project basis. Any IOU co-funding would be limited to the extent that the funding is within the IOU's Commission approved rate plan and that the advanced technologies being investigated by the R&D projects support their deployment in the IOU's capital plan. For TOs that are not co-funding the projects, they can support the projects through an advisory role, in-kind participation, or even choosing to host the demonstrations or piloting of the advanced technologies. The Commission should support incremental funds sought for these projects by NYSERDA and / or through IOU rate proceedings.

5. The R&D consortium will further investigate specific needs, capabilities, and plans for the establishment of a collaborative R&D and testing venue, first assessing existing resources in New York State, which could be utilized as part of the evaluation of currently new or future advanced technologies.

The group anticipates it will take at least six months to: establish the R&D consortium with the necessary governance structure and legal agreements in place; establish the criteria for project selection; identify the candidate projects for evaluation and selection; and select two to three projects from the project candidate list and prepare the work scope for each selected project. R&D projects typically run one to two years once the work scope is finalized.

2
THE PUBLIC SERVICE ORDER

STATE OF NEW YORK
PUBLIC SERVICE COMMISSION

At a session of the Public Service Commission held in the City of Albany on May 14, 2020

COMMISSIONERS PRESENT:

John B. Rhodes, Chair
Diane X. Burman
James S. Alesi
Tracey A. Edwards
John B. Howard

CASE 20-E-0197 - Proceeding on Motion of the Commission to Implement Transmission Planning Pursuant to the Accelerated Renewable Energy Growth and Community Benefit Act.

ORDER ON TRANSMISSION PLANNING PURSUANT TO THE ACCELERATED RENEWABLE ENERGY GROWTH AND COMMUNITY BENEFIT ACT

(Issued and Effective May 14, 2020)

BY THE COMMISSION:

INTRODUCTION

The State of New York has enacted the most aggressive climate policy legislation in the country through the Climate Leadership and Community Protection Act (CLCPA), signed into law by Governor Cuomo on July 18, 2019.[1] The CLCPA established specific targets for reducing greenhouse gas (GHG) emissions for all sectors of the economy and removing carbon produced by energy generation. Specifically, the CLCPA requires: (1) a 40% reduction in GHG emissions from 1990 levels by 2030 and an 85% reduction by 2050; (2) achieving a renewable electric generation target of 70% by 2030 and a 100% emissions-free electric supply by 2040; and (3) the addition of 9 Gigawatts (GW) of offshore

[1] Chapter 106 of the laws of 2019.

wind generation to the energy portfolio by 2035. The reach of these directives is transformative.

To achieve the CLCPA climate protection targets and in recognition of the fact that achieving the CLCPA climate protection targets requires restructuring and repurposing the State's electric transmission and distribution infrastructure, Governor Cuomo introduced the Accelerated Renewable Energy Growth and Community Benefit Act (the Act), as part of the 2020-21 Proposed Budget. The Governor subsequently signed a final version of the Act into law on April 3, 2020.[2] Among other things, the Act directs the Commission to develop and implement plans for future investments in the electric grid.This order reviews those legislative directives, immediately implements certain mandates, and outlines the additional actions the Commission plans to pursue to fulfill the objectives of the Act over the next several months.

BACKGROUND

The Act includes several provisions directing the Commission to ensure the electric grid will support the State's aggressive climate goals.First, Section 7(2) calls on the Commission, in consultation with other state agencies and authorities, the utilities,[3] and the New York Independent System Operator (NYISO), to conduct a "comprehensive study for the purpose of identifying distribution upgrades, local transmission upgrades, and bulk transmission investments that are necessary

[2] Chapter 58 (Part JJJ) of the laws of 2020.

[3] For the purpose of this proceeding, the term "utilities" will refer to Consolidated Edison of New York, Inc., Orange and Rockland Utilities, Inc., New York State Electric and Gas Corporation, Rochester Gas and Electric Corporation; Central Hudson Gas & Electric Corporation, and Niagara Mohawk Power Corporation d/b/a National Grid.

or appropriate to facilitate the timely achievement of the CLCPA targets ….”[4] The Act refers to this analysis as “the power grid study,” a term which we adopt here. An initial report of the findings and recommendations of the power grid study is required by December 31, 2020.

Second, the Act directs the Commission to commence two proceedings to advance needed projects identified through the power grid study.[5] One proceeding is to focus on establishing “a distribution and local transmission capital plan” for each utility.[6] These utility plans will describe and prioritize the local transmission and distribution “upgrades” that the Commission determines are “necessary or appropriate” to meet the CLCPA targets.[7] The Act provides that these upgrades will be implemented according to existing procedures under the Public Service Law.

The other planning proceeding mandated under the Act relates to the bulk transmission system.The Act requires a state-wide plan to identify and implement transmission-level

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[4] The statute does not define these key terms. For purposes of this discussion, we understand “local transmission” to refer to transmission line(s) and substation(s) that generally serve local load, and transmission lines which transfer power to other service territories and operate at less than 200 kV. However, as the Utilities consider the issues outlined in this order, we recognize that an alternative definition may emerge.

[5] Act, subsections (3) and (4).

[6] The Act also requires the Long Island Power Authority to establish a similar capital program to address local transmission and distribution upgrades in its service territory.

[7] The Act defines an “upgrade” to either the distribution or the local transmission system as a new facility or “an improvement, enhancement, replacement, or other modification” to existing equipment in the utility’s service territory “that facilitates achievement of the CLCPA targets.” Sections 7(d) and (e).

investments that are “necessary or appropriate to achieve the CLCPA targets.”The Act further specifies two different approaches to project implementation. Transmission investments that the Commission determines need to be “completed expeditiously” are referred to the New York Power Authority for development and construction. Other projects are to be selected for implementation through the NYISO’s public policy planning process.

DISCUSSION

These directives require us to revisit the traditional decision-making framework that the Commission and the utilities have relied on up to now for investing in transmission and distribution infrastructure. First, we must identify a strong portfolio of potential transmission and distribution projects that can support the development and delivery of renewable energy in order to support climate goals.   Second, the contribution of those projects to the State’s climate goals must now be expressly evaluated and weighed in system planning and project prioritization, while preserving the obligation of the State’s utilities to ensure safe, reliable and cost-effective service. Third, cost-containment and cost-recovery mechanisms must be reexamined, especially for projects that serve local reliability, as well as policy and systemic goals.Fourth, the planning and economic processes must continue to take fullest practical advantage of new technology and other innovation. The Commission will need to establish criteria to guide the utilities in making these evaluations and scheduling CLCPA-supporting projects.The Commission will have to explore and consider all available options to fund these essential investments. This latter task may require us to re-examine traditional utility cost recovery mechanisms and develop new approaches where existing mechanisms are deficient.

With this proceeding, we will begin to resolve these questions, initially in the context of the distribution and local transmission systems. We believe the State’s utilities are uniquely positioned to develop proposals for the revised decision-making framework we contemplate, as a starting point for broader stakeholder comment and discussions.

We note that, prior to the enactment of the Act, the Department of Public Service had already established working groups in collaboration with the utilities to address the policy, planning, and technological challenges to meeting the CLCPA targets. These proactive efforts are productive and useful, and this order intends to build on those efforts, as well as provide direction for future initiatives.

Local Transmission and Distribution Planning

The first task is to ensure the development of actionable local system upgrades through the power grid study, within the time frames required by the Act. We note that a comprehensive effort evaluating the future needs of the higher voltage transmission system is already underway.[8] We also note that the utility working groups have begun developing a study that should provide insight into other system needs.We direct the utilities to incorporate analyses in their study to identify the distribution and local transmission upgrades that may be “necessary or appropriate” to the timely achievement of CLCPA objectives. For these purposes, using the definitions provided in the Act, the relevant upgrades may be new facilities or

[8] The New York State Energy Research and Development Authority (NYSERDA) has initiated two studies looking at the future needs of the system. One is a study of the impact of offshore wind; the second looks at the transmission capabilities that will be needed to support the CLCPA goal of making the generation supply 100% renewable by 2040.

improvements or other changes to existing local transmission or distribution facilities located in a utility's service territory. The study to be undertaken by the utility working group (Utility Study) should consider the following:

1. Evaluate the local transmission and distribution system of the individual service territories, to understand where capacity "headroom" exists on the existing system;
2. Identify existing constraints or bottlenecks that limit energy deliverability;
3. Consider synergies with traditional Capital Expenditure projects - drivers of synergies could include aging infrastructure, reliability, resilience, market efficiency, and operational flexibility;
4. Identify least cost upgrade projects to increase the capacity of the existing system;
5. Identify potential new or emerging solutions that can accompany or complement traditional upgrades;
6. Identify potential new projects which would increase capacity on the local transmission and distribution system to allow for interconnection of new renewable generation resources; and
7. Identify the possibility of fossil generation retirements and the impacts and potential availability of those interconnection points.

With these elements included, the proposed Utility Study will serve as one component of the comprehensive power grid exercise called for in the Act. To ensure that the utilities conduct the study and make the results available in time for the Commission to take action within the Act's deadlines, we direct the utilities to update Staff on the progress of this effort at regular intervals and to provide preliminary results no later than August 1, 2020. We require the Utilities to submit the final results, including a list of potential distribution and local system upgrades, by November 1, 2020. We also ask the utilities, with the November filing, to provide their recommendations for integrating the identified projects into their ongoing capital programs.

In addition, in order to establish the continuing utility planning process mandated by the Act, we request the same working groups to develop practical proposals for the process that will guide the utilities' future investments.
Below we list the specific issues that we believe the utilities should explore.[9] We seek proposals on these topics, whether or not the utility participants achieve perfect consensus on all issues, as the starting point for additional deliberation. We intend to ask for public and stakeholder comment on these proposals and to act on them once we have heard from all interested parties.

The Commission seeks input and proposals for:

1. A transparent planning process, to be implemented by the utilities with as much consistency and interoperability as possible, that will identify additional projects on the distribution and local transmission systems that support achievement of CLCPA goals;
2. An approach to account for CLCPA benefits in the utilities' planning and investment criteria;
3. An approach to prioritizing any such recommended projects in the context of the utilities' other capital expenditures and the CLCPA time frames;
4. A benefit/cost analysis to apply in assessing potential investments in CLCPA upgrades to the distribution and local transmission systems, as well as any other criteria the utilities believe

[9] We expect the participants may identify other issues as they proceed; our list is intended as a guide to our primary objective, which is to respond to the Act's directives. We do not intend to restrict the scope of the working groups' responses to this Order.

5. should be applicable to evaluating these investments; and
6. Cost-containment, cost recovery, and cost allocation methodologies applicable to these investments and appropriate to the State's climate and renewable energy, safety, reliability, and cost-effectiveness goals.

Utility Models for Cost Recovery and Cost Allocation

The last task raises issues of ratemaking policy. We believe it will assist the working groups and other stakeholders to have our guidance on possible models for cost recovery and cost allocation for these types of projects. In providing this guidance, we assume that system studies carried out pursuant to this Order and in the future planning process will identify projects that contribute in different ways to the State's CLCPA goals.

First, we note that some distribution projects that are needed according to the utilities' traditional investment criteria — such as the like-kind replacement of aging assets – may simultaneously provide support for renewable integration or other CLCPA goals. We propose that the working groups consider whether the costs of such projects should be recovered from ratepayers, as they would be in the ordinary course. We refer to these as "business as usual" projects.

Second, we anticipate that some "business as usual" projects may present opportunities to expand or enhance the existing system's ability to realize the benefits of renewable resources. Where the utility can modify an already needed project to capture that additional benefit, a cost allocation methodology that recognizes the state-wide benefit of the modification might qualify as just and reasonable.[10]

[10] This assumes, of course, that the benefit can be identified and secured at a reasonable cost.

Third, we expect that the planning process may identify upgrades that would not be built according to traditional investment criteria, but address a specific need or limitation affecting progress towards the CLCPA goals. We recognize that no method for recovering the costs of these projects currently exists and that developing one will require resolving a number of issues. In particular, we anticipate that the utilities will have to define the benefits of such a project in a way that is fair and objectively quantifiable, and then develop mechanisms for recovering costs from the identified beneficiaries.   This latter recovery concept presents novel issues including how to identify who benefits from these CLCPA- targeted investments and by how much, as well as how to recover these costs. Nevertheless, anticipating that projects of this type may be identified in the future, we urge the utilities to propose solutions so that funding uncertainties do not hinder the State's climate goals.

Finally, we direct the utility working groups to file their proposals on the process and rate making topics listed above no later than October 5, 2020.   We anticipate seeking input from other stakeholders and intend to provide ample time for comment and deliberation following submission of the proposals.

Bulk Transmission Plan

As discussed above, the Act also requires the Commission to develop and implement a state-wide plan for building upgrades to the bulk power system, based on the results of the power grid study. While development of the bulk-power plan is not the topic of this action, we note that the studies already underway will show how the higher-voltage transmission system may need to be configured and expanded to meet climate objectives. However, results of those studies will not be available until the late fall of 2020.

In order to act promptly on the study results, we will initiate a second proceeding in the near future to establish decisional criteria for the bulk transmission planning and investments necessary to meet CLCPA mandates.Therefore, taking an approach similar to what we are doing here with respect to the distribution and local transmission systems, we direct Staff to identify the key issues that the Act requires us to resolve in developing the bulk investment plan, including the scheduling and prioritization of projects and the appropriate methodologies for funding these investments. We intend to utilize Staff's work as the basis for future stakeholder input on the Commission's implementation of the statute's bulk planning requirements. We fully expect that broad stakeholder input on these issues will be warranted. Our intent, as stated above, is to establish any decisional processes needed to support bulk system investments in time to act on the results of the power grid study early in 2021.

<u>The Commission orders</u>:

1. A proceeding is initiated to develop and consider proposals for implementing the provisions of the Accelerated Renewable Energy Growth and Community Benefit Act with respect to distribution and transmission upgrades, capital expenditures and planning, as discussed in the body of this order.

2. Consolidated Edison of New York, Inc., Orange and Rockland Utilities, Inc., New York State Electric and Gas Corporation, Rochester Gas and Electric Corporation; Central Hudson Gas & Electric Corporation, and Niagara Mohawk Power Corporation d/b/a National Grid will submit filings concerning distribution and transmission upgrades, capital expenditures and planning, as described in the body of this order.

3. In the Secretary’s sole discretion, the deadlines set forth in this order may be extended.Any request for an extension must be in writing, must include a justification for the extension, and must be filed at least one day prior to the affected deadline.

4. This proceeding is continued.

By the Commission,

(SIGNED) MICHELLE L. PHILLIPS

Secretary

3
UTILITY T&D ADVANCED TECHNOLOGIES WORKING GROUP CHARTER AND OUTLINE

The goal of the Utility T&D Advanced Technologies Working Group is to develop plans for the Utility T&D Investment Working Group to further the goals of the CLCPA by considering the New York State utilities / transmission owners and operators roles and opportunities for grid investments in advanced technologies. The working group will initially focus on developing research plans for new and underutilized technologies and innovations necessary in meeting New York's clean energy goals:

I. Initial focus will be on the transmission system, especially the sub-transmission system (138/115 kV) and below.
II. And initially the 70% renewable targets by 2030

To address these issues the working group will focus on the following objective:

Develop plans to study / evaluate, pilot / demonstrate and deploy new/advanced/underutilized technologies and innovations to: Increase power throughput, Increase grid flexibility, Increase hosting capacities, Increase system efficiencies, Reduce costs of system, etc., needed to meet goals. Answering questions (such as):

- Are there existing technologies that can improve the efficiency of the grid that are being underutilized?
- Are there R&D opportunities for new or emerging technologies?
- How should we organize the R&D effort?
- How do we coordinate work with other NY R&D stakeholders (EPRI, Universities, National Labs, DOE, ARPAe, etc.)?
- How do we coordinate work with the other working group teams (traditional solution & policy)?
- How will utilities integrate new technologies into planning and operations?

Outline:

Objective: Develop plans to study / evaluate, pilot / demonstrate and deploy new/advanced/underutilized technologies and innovations

Plan: (Completed by May 2020)

- Develop list of potential issues / needs / opportunities in meeting goals
- Develop list of potential solutions to address issues list
- Prioritize issue /solutions list based on potential impacts and technology ease and readiness

Outcomes: (Completed by November 2020)

- Develop information / use cases / case studies of potential solutions, investigate local national and global solutions
- Develop list of items not yet developed or in use
- Develop plans for tools, etc and process to vet new technologies through studies /evaluations, piloting / demonstrations and deployments.
- Develop plans for cost / benefit analysis of potential solutions
- Develop potential implementation plans

4
POTENTIAL ISSUES AND SOLUTIONS

Item #	Potential Issue	Potential Solutions - NYPA	Potential Solutions - Con Edison	Potential Solutions - National Grid	Potential Solutions - Central Hudson	Potential Solutions - Orange & Rockland	Potential Solutions - Avangrid	Potential Solutions - PSEG-LI	Potential Solutions - LIPA
3	Long term seasonal power balancing - As we increase % of clean energy we could run into seasons where generation is not sufficient.			NG - NREL has an expert that can speak to seasonal loading his name is Ben Kroposki.					
4	Loss of external tie lines effect on system strength and reserves	NYPA - Enhanced studies for more accurately evaluating proper level of reserves							
5	Harmonic & Noise issues	NYPA - Start performing harmonic analysis modeling and studies (potentially as part of interconnection process) NYPA - Install harmonic monitoring systems at key locations and monitor system harmonics in a systematic, continuous way						PS- Leverage EPRI's effort Evaluation monitoring harmonics/power quality issues PS- Identify advanced filtering technologies to filter harmonics.	
6	Fast transient phenomena caused by HVDC controls or inverters	NYPA - Modeling and studies involving HVDC details and proper fine tuning of inverters and controls.	CE - Enhanced modeling studies, learnings from European best practices					PS- Future study to capture that PS- Leverage NERC industry effort related on IBR on weak system	
7	Forced oscillation problems with a large number of inverter based resources	NYPA - Invest in real-time oscillation monitoring and detection systems, such as systems based on PMU data (e.g. EPG's RTDMS monitoring system) NYPA - Modeling and studies involving oscillation damping schemes NYPA - Wide-Area control schemes (versus local-feedback control) of FACTS and DERs for oscillation damping and fault-tolerant grid operation NYPA - Advanced modeling and simulation tools and testing capabilities to allow for proper configuration of inverter controls and troubleshooting for resolving forced oscillation issues.							
8	Inability to meet reserve requirements due to proliferation of DER	NYPA - Perform studies for evaluating proper level of reserves considering DER models						PS- Coordinate with NYISO on the system reserve PS- System study to evaluating the system reserve	
9	Outage scheduling for DERs, especially aggregated behind the meter solar not currently subject to NYISO outage scheduling criteria	NYPA - Data analytics for disaggregation (of BTM loads) coupled with stochastic models for resource availability for DERs based on historical performance/availability data. This may allow for estimation of expected availability of DER. NYPA - Coordination of outage planning via an expanded NYISO process at the aggregator level.							
10	Cybersecurity of third party DER sites not subject to NERC CIP	NYPA - Regulatory changes and/or establish cyber procedures for DER integration based on existing cyber technologies.							
11	System restoration black start with high penetration of DERs	NYPA - Expanded procedures for using DERs as a part of the restoration process (backbone and local blackstart plans) NYPA - Using DER, specifically storage with grid-forming capability, for faster system restoration….(1. restoration using IBR for faster restoration - distributed or grid scale 2. grid forming inverters with hybrid storage to provide grid services - fluctuations etc.) NYPA - TSO-DSO (Bulk System Generation in coordination for ADMS) for faster black-start and system restoration							
12	Microgrid resiliency with safe island operations	NYPA - Fast switching and transfer switching technologies .. Transfer schemes with no backfeed to utility and no re-switching without utility approval. (look essential SEL and S&C platforms)							
13	System reserve requirements	NYPA - Enhanced studies for more accurately evaluating proper level of reserves		NG - NYSRC-ICS develops yearly IRM, which will increase drastically with added renewable generation				PS- Coordinate with ISO on the system reserve PS- System study to evaluating the system reserve	

Item #	Potential Issue	Potential Solutions - NYPA	Potential Solutions - Con Edison	Potential Solutions - National Grid	Potential Solutions - Central Hudson	Potential Solutions - Orange & Rockland	Potential Solutions - Avangrid	Potential Solutions - PSEG-LI	Potential Solutions - LIPA
14	Radial lines resiliency problem	NYPA - Energy storage and/or potential DER application for improving resiliency and deliverability in such areas. Use incentives/programs for creating MGs with DERs in such areas		NG - Energy storage at the end of radial lines could be a solution to the resiliency issue we raised.					
15	Relay protection & coordination due to some renewables having limited short circuit capabilities	NYPA - Investigate potential new relaying technologies such as traveling wave relays that do not depend on fault current levels.	CE - Characterization of short circuit rating for IBRs; better understanding of capabilities/behavior						
16	Electromagnetic pules impacts	NYPA - Look for input and recommendations from the EPRI EMP working group studies	CE - Enhanced lab & field testing (of IBRs-?) for EMP events					PS- Leverage NERC effort	
17	Increasing hydro imports	NYPA - Develop new HVDC transmission systems at preferred interconnection points close to load centers. NYPA - New interconnections using variable frequency transformers. NYPA - Investigate low-frequency AC solutions for external interconnections NYPA - Fast generation reserves and control schemes to alleviate the impact of single contingencies and limit transfer capabilities along single lines.		NG - Turn the Champlain-Hudson Power Express into a "local" with converter stations at Plattsburgh, Crown Point, New Scotland, other points south					
18	Load factor changes to cables due to changes in system	NYPA - Invest in installations of cable monitoring systems for asset health management.						PS- System study for 1.0 load factor impact PS- Dynamic Rating system for the transmission circuits and give operation guidance in order to maintain the same load factor. PS- Identify public policy project to address the thermal constraints	
19	Need more from static line rating - dynamic line rating	NYPA - Start using weather-dependent or dynamic rating of critical lines—NYISO acceptance and implementation of DLR in the SCUC for DAM and RTM							
20	Minimize impacts of all electrification of energy systems	NYPA - Turning Electrification to an opportunity for the grid- virtual storage…. (e.g. Heat pump in buildings, new loads as potential storage.)…. Intelligent Demand Side Management Systems with enhanced capabilities for grid NYPA - V2G fleet services (e.g https://bit.ly/2J9QDe8) NYPA - Acceptance and advanced protection and safety methods for V2G (https://bit.ly/2UxLj9M)	CE - This issue is very broad and can have many solutions, such as DER, energy storage and energy efficiency. Realistic target date past 2030						
21	Enclosed wire technology to min impacts of temp/ etc and reduce need to reconductor line	NYPA - Using dynamic line ratings for improving thermal limits of lines. Typical commercially available technologies include: Lindsey, Ampacimon, LineVision, EDM, Pfisterer, etc.)						PS- Dynamic Rating system for the transmission circuits and give operation guidance in order to maintain the same load factor.	
22	Transformer overloads - new coolant to increase transformer ratings - following valid design contingencies	NYPA - Look into any new forced cooling technologies, such as forced air cooling, oil circulation, or new coolants. NYPA - Real-time transformer condition and ambient monitoring for dynamic transformer load rating.	CE - Thermal lab & field testing; finite element analysis to measure surface temperature thermal pattern				A - well built structure around transformer to minimize ambient effect on rating new coolant or replacing existing fans with efficient fans to improve rating		

Item #	Potential Issue	Potential Solutions - NYPA	Potential Solutions - Con Edison	Potential Solutions - National Grid	Potential Solutions - Central Hudson	Potential Solutions - Orange & Rockland	Potential Solutions - Avangrid	Potential Solutions - PSEG-LI	Potential Solutions - LIPA
23	Unbottling of constrained generation	NYPA - For thermally constrained situations potentially using DLR in combination with FACTS flow controllers such as SSSC or distributed FACTS (e.g. Smart Wires). For voltage or stability constraints using other FACTS devices such as SVCs, STATCOM to improve transmission transfer capabilities.		NG - Online monitoring and asset health sensors – this would fall under the asset utilization and predictive maintenance solutions.				PS- system reinforcement (including tie-line) PS- Resource curtailment PS- Battery installation to pair up with the renewable	
24	More effective utilization of existing transmission capacity	NYPA - For thermally constrained situations potentially using DLR in combination with FACTS flow controllers such as SSSC or distributed FACTS (e.g. Smart Wires). For voltage or stability constraints using others FACTS devices such as SVCs, STATCOM to improve transmission transfer capabilities. NYPA - Use of phase angle regulators to adjust flows, mainly on interconnection lines. NYPA - Use FACTS and distributed FACTS for flow control and deliverability enhancement. NYPA - Improve energy delivery by maximizing ROW using "BOLD" Transmission Tower structures per the info received from DPS. NYPA - Use new high-temperature, low-sag (HTLS) conductors when reconductoring lines (e.g. ACCC, ACCR, etc.) NYPA - Investigate new insulating materials that could allow closer proximity between conductors (especially in lower voltage lines, line substansmission) NYPA - Share overhead line ROW with underground cables to push more power through existing corridors (e.g. using horizontal directional drilling (HDD))							
25	Maximize utilization of existing right of ways	NYPA - For thermally constrained situations potentially using DLR in combination with FACTS flow controllers such as SSSC or distributed FACTS (e.g. Smart Wires). For voltage or stability constraints using others FACTS devices such as SVCs, STATCOM to improve transmission transfer capabilities. NYPA - Use of phase angle regulators to adjust flows, mainly on interconnection lines. NYPA - Use FACTS and distributed FACTS for flow control and deliverability enhancement. NYPA - Improve energy delivery by maximizing ROW using "BOLD" Transmission Tower structures per the info received from DPS. NYPA - Use new high-temperature, low-sag (HTLS) conductors when reconductoring lines (e.g. ACCC, ACCR, etc.) NYPA - Investigate new insulating materials that could allow closer proximity between conductors (especially in lower voltage lines, line subtransmission) NYPA - Share overhead line ROW with underground cables to push more power through existing corridors (e.g. using horizontal directional drilling (HDD))						PS- LIPA is going to fully utilize the underground ROW as well which is pretty close to the limits for utilizing the ROW. For any future system reinforcement, It will require rights to expand the ROW	

Item #	Potential Issue	Potential Solutions - NYPA	Potential Solutions - Con Edison	Potential Solutions - National Grid	Potential Solutions - Central Hudson	Potential Solutions - Orange & Rockland	Potential Solutions - Avangrid	Potential Solutions - PSEG-LI	Potential Solutions - LIPA
26	Bottleneck in transmitting power off Long Island to New York state	NYPA - For thermally constrained situations potentially using DLR in combination with FACTS flow controllers such as SSSC or distributed FACTS (e.g. Smart Wires). For voltage or stability constraints using others FACTS devices such as SVCs, STATCOM to improve transmission transfer capabilities. NYPA - Use of phase angle regulators to adjust flows, mainly on interconnection lines. NYPA - Use FACTS and distributed FACTS for flow control and deliverability enhancement. NYPA - Improve energy delivery by maximizing ROW using "BOLD" Transmission Tower structures per the info received from DPS. NYPA - Use new high-temperature, low-sag (HTLS) conductors when reconductoring lines (e.g. ACCC, ACCR, etc.) NYPA - Investigate new insulating materials that could allow closer proximity between conductors (especially in lower voltage lines, line subtransmission) NYPA - Share overhead line ROW with underground cables to push more power through existing corridors (e.g. using horizontal directional drilling (HDD)) NYPA Use of more underground cabling and deliver power to optimal points of interconnection to bypass constraints (deliver offshore wind directly to NYC at points past Long Island?)						PS- system reinforcement (including tie-line) PS- Resource curtailment PS- Battery installation to pair up with the renewable	
27	Future build out of regulations on GIS gases for expansion	NYPA - Investigate use of SF_6 alternatives such as AirPlus and Novec dielectric fluids as alternatives to SF_6. (https://bit.ly/2Qocdj2 and https://bit.ly/2QrvK1X) NYPA - New SF_6-free 420kV CB in development. (https://bit.ly/2QvJhWl)						PS- acquire land for additional space near Current substation	
28	Identification and alleviation of transmission bottlenecks that could restrict deliverability of renewables	NYPA - Perform studies for optimal interconnection points See items under 25 and 26 depending on the details of the issue						PS- system reinforcement (including tie-line) PS- Resource curtailment PS- Battery installation to pair up with the renewable	
29	Frequency response and loss of inertia	NYPA - Using the PMU data for online system inertia monitoring. NYPA - Creating synthetic inertia by wind farms using inverter controls. NYPA - Using hybrid energy storage at highly variable energy resources to stabilize their output and reduce power fluctuations due to generation fluctuations. (https://bit.ly/33rVu3y)							
30	Unpredictability of under frequency load shed	NYPA - Using data driven/measurements schemes to better understand load compositions and enhance load shedding schemes. NYPA - Dynamic load modeling using PMU or other measurement data for more accurate and adaptive load shedding (D factor in conventional UFLS)							
31	Frequency control under large fluctuation of generation	NYPA - Using the PMU data for online system inertia monitoring. NYPA - Creating synthetic inertia by wind farms using inverter controls. NYPA - Using hybrid energy storage at highly variable energy resources to stabilize their output and reduce power fluctuations due to generation fluctuations. (https://bit.ly/33rVu3y) NYPA - Virtual Power Plants using DERs. (https://bit.ly/2UhTBCn ; https://bit.ly/3a0TKAN ; https://bit.ly/2U4xwIV) NYPA - Wide-Area control schemes (versus local-feedback control) of FACTS and DERs for oscillation damping and fault-tolerant grid operation							
32	Variability of power flow caused by rapid variations in large scale energy storage providing NYISO regulation service, fast response to maintain frequency /voltage								

Item #	Potential Issue	Potential Solutions - NYPA	Potential Solutions - Con Edison	Potential Solutions - National Grid	Potential Solutions - Central Hudson	Potential Solutions - Orange & Rockland	Potential Solutions - Avangrid	Potential Solutions - PSEG-LI	Potential Solutions - LIPA
33	Decline in system inertia - solutions to existing problems should favor solutions that add to system inertia	NYPA - Using the PMU data for online system inertia monitoring. NYPA - Creating synthetic inertia by wind farms using inverter controls. NYPA - Using hybrid energy storage at highly variable energy resources to stabilize their output and reduce power fluctuations due to generation fluctuations. (https://bit.ly/33rVu3y)					A - favor SVCs instead of capacitor for reactive support solutions to existing voltage problems	PS- Future study to capture that PS- Leverage NERC industry effort related on IBR on weak system	
34	Loss of inertia can increase power oscillations	NYPA - Invest in real-time oscillation monitoring and detection systems, such as systems based on PMU data (e.g. EPG's RTDMS monitoring system) NYPA - Modeling and studies involving Oscillation damping schemes NYPA - Wide-Area control schemes (versus local-feedback control) of FACTS and DERs for oscillation damping and fault-tolerant grid operation						PS- Future study to capture that PS- Leverage NERC industry effort related on IBR on weak system	
35	Could better operational controls allow for a less strict planning constraints /restrictions	NYPA - Using fast wide-area control schemes (closed loop at the system operator level) such as faster secondary frequency control and voltage control (e.g. with reliable communication schemes, faster responding energy resources, fast responding voltage control, special protection schemes)							
36	Impacts of wide scale DERs - wide scale tripping, fast reclose schemes, backfeeding issues	NYPA - Fast switching and transfer switching technologies .. Transfer schemes with no backfeed to utility and no re-switching without utility approval. (look essential SEL and S&C platforms)						PS- Expand beyond the NERC reliability guideline on DERs	
37	Better controls across the board	NYPA - Using fast wide-area control schemes (closed loop at the system operator level) such as faster secondary frequency control and voltage control (e.g. with reliable communication schemes, faster responding energy resources, fast responding voltage control, special protection schemes)							
38	Intermittency of renewables impacts, with more coming in	NYPA - Cutting-edge forecasting tools such as LoadSEER and WattPlan Grid for accurate DER forecasting. (https://bit.ly/2QqRivS) NYPA - Using storage, like batteries, for congestion relief and ancillary services and reserves, in lieu of transmission upgrades. Investigate options of operation of storage either as a generation asset providing ancillary services or as a transmission access used for transmission operations such as congestion relief, voltage support, etc.							
39	Maintain operations and system restoration during "black sky" event and loss of SCADA	NYPA - Investigate options for backup or alternate (out-of-band) communication schemes (e.g. radio networks, analog telemetry, etc.)	CE - Addressed by DOE-EPRI SOLACE project; utilizing 'grid forming' inverters to provide resiliency http://www.ece.utexas.edu/news/ut-austin-develop-next-generation-grid-forming-pv-inverters-enhance-resilience-power-grid						
40	Controls - Loss of load minimizing, traditional , build redundancy to avoid loss,	automatic bus transfer reconfiguration, study to optimally place sectionalizers							
41	Long AC cable connected to weak point of grid - harmonics issue	NYPA - Evaluate both AC and DC options for interconnections at long distances NYTIA - Start performing harmonic analysis modeling and studies (potentially as part of interconnection process) NYPA - Look into active/passive advanced filtering technologies to filter harmonics. NYPA - Install and operate harmonic measurement and monitoring systems.						PS- Leverage EPRI's effort PS- Evaluation monitoring harmonics/power quality issues PS- advanced filtering technologies to filter harmonics.	

Item #	Potential Issue	Potential Solutions - NYPA	Potential Solutions - Con Edison	Potential Solutions - National Grid	Potential Solutions - Central Hudson	Potential Solutions - Orange & Rockland	Potential Solutions - Avangrid	Potential Solutions - PSEG-LI	Potential Solutions - LIPA
42	Can monitoring and controls systems computationally handle a tenfold increase in number of generators	NYPA - Investigate using new computing technologies such as high-performance computing (HPC) environments, use of graphics processing unit (GPU) clusters, use of supercomputers at research institutions, or improved algorithms for faster and scalable computations when solving simulation or optimization problems. Transfer knowledge from other areas that deal with large-scale problems, like data analytics, aerospace industry (airline scheduling), astrophysics, nuclear physics, etc.							
43	Dispatch constraints - mostly thermal - DER is causing costly transmission upgrades due to shoulder conditions	NYPA - Energy storage solutions or improved curtailment options NYPA - Invest in high-temperature, low-sag conductors if ending up with performing upgrades.							
44	Infrequent thermal & voltage variations on unsecured T&D facilities - ex; batteries charging during peak load							PS- NYISO to look into the market rule for the energy storage PS- Consider limiting the charging schedule of an energy storage in an IA	
45	Better communications for control, monitoring, protection	NYPA - Invest in the development of a better, faster, reliable/redundant, and secure communication backbone using fiber, microwave, and private cellular infrastructure. Coordinate deployments so that multiple utilities can benefit from deployed infrastructure when possible instead of each utility deploying their own independent infrastructure.	CE - Applying IEEE 1547-2018 standards with comm's protocols for DERs (DNP3, Sunspec, Modbus, IEEE 2030.5, etc) - various efforts are under way (EPRI, et al) looking at 'gateways' by which DERs can effectively communicate M&V to local SCADA systems						
46	Transformer load tap changers - issue due to cycling a lot	NYPA - Adoption of data driven approaches to reduce frequency of tap changes or and quantify wear and tear. NYPA - Use local voltage and power factor correction devices to avoid always using tap changers for control. NYPA - Investigate the case of solid state transformers that could provide similar capabilities with no moving parts.							
47	SF_6 alternatives needed - due to phasing out	NYPA - Investigate use of SF_6 alternatives such as AirPlus and Novec dielectric fluids as alternatives to SF_6. (https://bit.ly/2Qocdj2 and https://bit.ly/2QrvK1X) NYPA - New SF_6-free 420kV CB in development. (https://bit.ly/2QvJhWl)						PS- acquire land for additional space near current substation for open air conversion	
48	High pressure fluid filled underground cables - dielectric fluid leaks - need prediction monitoring, leak minimization	NYPA - Advanced monitoring technologies for underground cables that include pressure monitoring, leakage detection, cathodic protection, etc. (e.g. USi system)							
49	Old substations - is it worth a full rebuild or can it be retired for alternative technologies								
50	Eliminate SF_6	NYPA - Investigate use of SF_6 alternatives such as AirPlus and Novec dielectric fluids as alternatives to SF_6. (https://bit.ly/2Qocdj2 and https://bit.ly/2QrvK1X) NYPA - New SF_6-free 420kV CB in development. (https://bit.ly/2QvJhWl)						PS- acquire land for additional space near current substation for open air conversion	
51	Governance to oversee/manage all the sensor data, communication requirements - increasing amounts of data /sensors	NYPA - Data management and data exchange technologies and systems (this might be more of a data governance issue rather than technology issue)	CE - Distribution Automation/ utilize data concentrators and distributed/networked control schemes						
52	Technical issues when having IBR, power electronic devices - obtaining EMT models for stability, transients, controls	NYPA - Adoption of different modeling and analysis tools and technologies and study capabilities.	CE - Enhanced modeling studies per specific use case					PS- expand on the previous EPRI model standardization	
53	Lack of appropriate knowledge/experience working with IBRs at utilities	NYPA - Training simulators in new test/training facilities NYPA - Knowledge transfer from other areas worldwide via information/experience exchanges							
54	Distribution standards have hard limits for new interconnections	NYPA - Adaptation of existing standards e.g. IEEE 1547 for use at the transmission level							

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55	Need better forecasting of wind. Irradiance for planning and procurement of generation in market	NYPA - Adoption and utilization of better forecasting tools, such as LoadSEER and WattPlan Grid for accurate DER forecasting. https://bit.ly/2QqRivS							
56	Dynamic 3 phase, 8760 hrs/yr models at distribution levels	NYPA - Utilization of quasi-static time-series power flow to capture renewable generation variables, controllable storage, and controllable loads		NG - Regarding the issues that were raised on modeling and predicting DER behaviors, our protection team has done a lot of work in this field that can speak to how passive islanding protection of DER resulted in the large outage in the UK and how most inverter models were found to be inaccurate.					
57	Visibility and controls of DERs especially aggregated behind the meter solar	NYPA - Deployment of smart meters and other devices (e.g microPMUs) for obtaining more measurements and improving visibility. NYPA - Utilization of disaggregation methods for estimating % of load and % of generation at a feeder or circuit.	CE - Development of DERMS platform with ability to capture & store varying SCADA & AMI data to produce more granular state estimation inclusive of DERs						
58	Alarm mgmt at control center	NYPA - Artificial intelligence applications for better coordination of alarm management. EPRI has done a lot of work in alarm management, but this might be mainly by their generation sector.							
59	Existing T & sub T lines will be tapped or segmented, substantially because new gen fleet will be more dispersed	NYPA - Utilize sectionalized modeling of lines in various studies							
60	Smart siting of DER and storage		CE - Addition of demo projects, careful attention to sizing of ES with grid impact/contribution						
61	Wind & solar energy profiles connected to system	NYPA - Organized historical data collection and adoption and utilization of forecasting tools.							
62	Coordination of siting & storage - operating regime optimization								
63	Accurate DER forecasting	NYPA - Organized historical data collection and adoption and utilization of forecasting tools.							
64	With more severe weather, we expect more weather extremes	NYPA - Perform system resiliency studies for extreme weather or other natural disaster scenarios to optimally strengthen the system and improve resiliency. NYPA - Deploy system reconfiguration devices and mechanisms that could be used to reduce the impact of contingencies and maintain load services. NYPA - Development of microgrid to improve resiliency	CE - Integration of enhanced weather forecast modeling capabilities with OMS platforms and other DMS/DERMS systems						
65	Requirements for studies not within the capabilities of conventional planning tools and skill sets - snap shots vs variable in loads, transmission security calcs	NYPA - Utilization of quasi-static time-series power flow to capture renewable generation variables, controllable storage, and controllable loads		NG - Develop additional capabilities at AGILe					

Item #	Potential Issue	Potential Solutions - NYPA	Potential Solutions - Con Edison	Potential Solutions - National Grid	Potential Solutions - Central Hudson	Potential Solutions - Orange & Rockland	Potential Solutions - Avangrid	Potential Solutions - PSEG-LI	Potential Solutions - LIPA
66	Existing power issue of a large offshore scale injection (Sending power upstate)	NYPA - For thermally constrained situations potentially using DLR in combination with FACTS flow controllers such as SSSC or distributed FACTS (e.g. Smart Wires). For voltage or stability constraints using others FACTS devices such as SVCs, STATCOM to improve transmission transfer capabilities. NYPA - Use of phase angle regulators to adjust flows, mainly on interconnection lines. NYPA - Use FACTS and distributed FACTS for flow control and deliverability enhancement. NYPA - Improve energy delivery by maximizing ROW using "BOLD" Transmission Tower structures per the info received from DPS. NYPA - Use new high-temperature, low-sag (HTLS) conductors when reconductoring lines (e.g. ACCC, ACCR, etc.) NYPA - Investigate new insulating materials that could allow closer proximity between conductors (especially in lower voltage lines, line subtransmission) NYPA - Share overhead line ROW with underground cables to push more power through existing corridors (e.g. using horizontal directional drilling (HDD))						PS- system reinforcement (including tie-line) PS- Resource curtailment PS- Battery installation to pair up with the renewable	
67	Stability issues with inverter-based connected resources - Decreased system inertia due to increased IBR penetration and displacement of conventional synchronous generators. Increased system impedance (decreased short-circuit strength) due to increased IBR penetration and displacement of conventional synchronous generators. Obtaining and managing modeling information, including EMT models, for complex IBR and HVDC systems.	NYPA - Using the PMU data for online system inertia monitoring. NYPA - Creating synthetic inertia by wind farms using inverter controls. NYPA - Using hybrid energy storage at highly variable energy resources to stabilize their output and reduce power fluctuations due to generation fluctuations. (https://bit.ly/33rVu3y)	CE - Constructing detailed study with advanced models to observe such cases and develop recommendations					PS- Leverage NERC industry effort related on IBR on weak system	
68	System stability impacts of potential wide-scale tripping of distributed energy resources (DER)	NYPA - Using fast wide-area control schemes (closed loop at the system operator level) such as faster secondary frequency control and voltage control (e.g. with reliable communication schemes, faster responding energy resources, fast responding voltage control, special protection schemes)						PS- Based on recent system events, continue to leverage the efforts on what has been done by NERC - voltage ride through etc.	
69	System reserve requirement	NYPA - Enhanced studies for more accurately evaluating proper level of reserves		NG - NYSRC-ICS working on this (NYISO whitepaper)				PS- Coordinate with ISO on the system reserve PS- System study to evaluating the system reserve	
70	Wind and solar energy profile connected to LIPA's system	NYPA - Organized historical data collection and adoption and utilization of forecasting tools.							
71	Symptoms/issues of the system with a ubiquity of connected power electronic devices (Harmonic resonance, SSTI, Transient Voltage Recovery	NYPA - Appropriate modeling and studies to identify potential symptoms and issues on a case by case basis. NYPA - Invest in monitoring systems that could provide real-time information and additional data, such as transient voltage recordings, harmonic content, etc.							
72	Breaker adequacy of a weak system with inverter based resources or resources connected via long ac cables. DC Breaker may be needed. Zero crossing on the AC	NYPA - Could also investigate potential advantages of low-frequency AC transmission in such cases.							
73	Impact of energy storage (charge/discharge cycles) to the lifetime of equipment in the grid. Does this cause a flat lining of the system load/Thermal rating? If so, does this cause a revision to cable/wire ratings necessitating more transmission lines. Need for dynamic ratings systems for system operator							PS- System study for 1.0 load factor impact PS- Dynamic Rating system for the transmission circuits and give operation guidance in order to maintain the same load factor. PS- Identify public policy project to address the thermal constraints	

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74	Impact of electrification of everything to the grid - Winter peak utility -Need for more transmission lines - Thermal issues and ratings	NYPA - Addressed by various items above							
75	Variability in voltage and power flow caused by rapid variations of large-scale energy storage providing NYISO regulation service - Fast ramping to maintain frequency vs the voltage								
76	Interactions between power electronic systems, including inverter-based resources (IBR), HVDC transmission, and FACTS devices.	NYPA - Proper studying, testing in a lab environment. Create an environment that would allow proper experimentation and testing prior to deployment, such as the AGILe lab,	CE - Hardware in the loop testing to better understand interoperability of said devices (currently studying smart inverter settings and local interaction via EPRI-NYSERDA 'smart inverter AI/ML' project where we (ConEd) are a technical advisor)					PS- Sharing/Coordination on detailed simulation system model	
77	Increased requirements for studies not within the capabilities of conventional planning tools and skill sets. Snap shot currently vs variable in load. Transmission security simulation tool – considers variability of load (load cycle) and generation/resource	NYPA - Utilization of quasi-static time-series power flow to capture renewable generation variables, controllable storage, and controllable loads						PS- Working with Resource Planner and Industry to identify additional tools	
78	Adaptation of planning procedures and practices for radically different load and generation scenarios (e.g., maximum renewable output coincident with minimum load demand). Necessity of considering distribution systems to a greater degree in transmission planning and analysis.			NG - Utilize AGILe lab for fast-turnaround modelling (NYSERDA blanket funding)				PS- Working with the industry to identify advanced tools to correlate the system forecast with the renewable energy output PS- engage with renewable energy developer to understand the ramping and curtailment capability	
79	California like restrictions on GREEN GASES in NY that may affect buildout of transmission lines and substations (138 kV open air to 345 kV GIS buildout)								
80	DER-hot line reclose blocking to avoid transfer trip - Fast reclose schemes on Long Island	NYPA - New protection schemes and practices							
81	Backfeeding from distribution to transmission system	NYPA - New control schemes and operating practices. Develop new schemes to accommodate backfeed or specific desirable conditions.							

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82	Max utilization of existing asset and ROWs at Trans and Sub-Trans and Dist levels Thru Re-Building and/or Reconfiguring and making the best use of new Technologies when feasible and economical.	NYPA - For thermally constrained situations potentially using DLR in combination with FACTS flow controllers such as SSSC or distributed FACTS (e.g. Smart Wires). For voltage or stability constraints using others FACTS devices such as SVCs, STATCOM to improve transmission transfer capabilities. NYPA - Use of phase angle regulators to adjust flows, mainly on interconnection lines. NYPA - Use FACTS and distributed FACTS for flow control and deliverability enhancement. NYPA - Improve energy delivery by maximizing ROW using "BOLD" Transmission Tower structures per the info received from DPS. NYPA - Use new high-temperature, low-sag (HTLS) conductors when reconductoring lines (e.g. ACCC, ACCR, etc.) NYPA - Investigate new insulating materials that could allow closer proximity between conductors (especially in lower voltage lines, line subtransmission) NYPA - Share overhead line ROW with underground cables to push more power through existing corridors (e.g. using horizontal directional drilling (HDD))		NG - New transmission tower designs - ex Transource They also presented their design a few years ago to National Grid. Below were some initial observations back then; • The structures have a wider footprint and therefore requires a larger ROW Width, which we rarely have. They show the phases being a 4ft wider than "typical". • the EMF comparison to typical double circuit with phasing of A-B-C/A-B-C but we would typically look to configure A-B-C/C-B-A to reduce EMF. I don't doubt the EMF is lower with a delta but it'd be interesting to see if you really achieved much benefit on EMF compared to typical A-B-C/C-B-A configuration. • This design is not live line compatible • Overall, we recall that the cost of using their design was extremely high. Symmetrical conductor bundling; high-phase order; hybrid AC/DC corridors; ultra-low-frequency transmission					
83	Start at Renewable-Rich areas when in lower voltage areas and work our way to the EHV system to ensure deliverability.								
84	Coordination and siting of STORAGE – Operating regime optimization	NYPA - Besides batteries also look into new pumped-hydro sites including variable-speed to be developed. Could be small-scale using existing reservoirs, like at existing water infrastructure.							
85	Smart STING of DER and Storage (POI optimization)	Already covered by several of the above							
86	Controls across the board are extremely important	Already covered by several of the above		NG - Needed to harmonize generation, power flows, and dispatchable load					
87	Resiliency (micro grid capabilities and SAFE islanded operation without the grid)	Already covered by several of the above							
88	Accurate DER forecasts are very valuable and important	Already covered by several of the above							
89	Frequency regulation	Already covered by several of the above							
90	Volt/Var regulation	Already covered by several of the above							
91	Operating Reserves	Already covered by several of the above							
92	Load-following								
93	Oscillation prevention and control	NYPA - Invest in real-time oscillation monitoring and detection systems, such as systems based on PMU data (e.g. EPG's RTDMS monitoring system) NYPA - Source of oscillation detection tools NYPA - Oscillation cause analysis using historical (PMU) data. NYPA - Modeling and studies involving oscillation damping schemes NYPA - Wide-Area control schemes (versus local-feedback control) of FACTS and DERs for oscillation damping and fault-tolerant grid operation NYPA - Advanced modeling and simulation tools and testing capabilities to allow for proper configuration of inverter controls and troubleshooting for resolving forced oscillation issues.							

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94	Renewables impact on system operations is unpredictable, posing challenges to system operations: power dispatch, frequency and voltage control.		CE - Development of near-real time weather prediction methods and modeling/simulation tools. Grid-scale energy storage. Use of V2G.						
95	Increased amount of data from AMI and from field sensors - substations, transmission, distribution		CE - Data analytics, Artificial Intelligence						
96	Aging equipment: increasing cost of O&M and infrastructure replacement; increasing catastrophic equipment failures		CE - Automated inspection using robotics with IR and PD tools to detect incipient faults						
97	Environmental impact from dielectric fluids and SF_6 emissions		CE - Adoption of alternative materials						
98	Increasing loads from EV		CE - Use of smart charging technology						
99	Training of new generation of workforce		CE - Use of Virtual Reality, AR and XR for training						
100	Creating zero-harm environment		CE - Robotics for switching, cable splicing, inspections, maintenance.AR applications for verification of operational steps - "digital peer-check" Wearable safety devices						
101	"Black sky" event - loss of SCADA: a) maintain operation; b) system restoration - black start		CE - "Spare tire" program						
102	Alarm management at control center		CE - AI for alarm management (EPRI project)						
103	less visibility into existing system (lower kVs)						A - Tollgrades sensor technology		
104	Line overloads following valid design contingencies						A - wide scale DLR to be used in operations horizon A - line coating technology to minimize impact on ambient conditions		
105	Adequacy of load flow programs used to establish smart inverter settings + model verification & parameterization requirements		CE- Conducting an evaluation/cross comparison of various loadflow software that can aide with establishing smart inverter settings per IEEE1547 (for distribution) and P2800 (for transmission) that can either augments or replace in-house tools/methods/processes (OpenDSS, PowerFactory, CYME, Synergy, etc.). Also providing needed insights on proper model verification & parameterization requirements.						
106	To what extent can "default" inverter settings be used without causing adverse effects on either T&D systems		CE - Perform transmission level and distribution level sensitivity simulations/analyses to determine at what level of DER penetration (on either systems, and in what combination) can “default inverter settings” be allowed without causing adverse effects on either system; considering voltage & frequency stability + other BPS ride-through requirements where loss of inertia from DER trip outs can cause system (frequency) instability. Understanding return to service behavior following a trip.						
107	Tying Networks for Grid Resiliency/load relief using DC link		CE - Develop detailed model of DC link design tying 2 networks together with smart inverters to alleviate network/feeder constraints. Can lead to a full demo as well.						

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108	Need for advanced modeling of Offshore Wind renewables, to understand interconnection requirements		CE - Develop detailed Off-Shore Wind model to better understand interconnection requirements including inverter settings						
109	Updated relay protection schemes to incorporate DERs on T&D		CE - Basing off of simulation results, develop a framework for a new/modified substation relay protection philosophy/schemes to accommodate high penetration of DERs/IBRs						
110	Addressing NERC concerns about modeling requirements for IBRs; especially relating to momentary cessation		CE - Develop model to represent momentary cessation (per NERC alert/IG): Momentary cessation blocking threshold; Recovery delay of inverter current; Active power ramp rate during recovery; Number of successive events; Modes: Normal; Block; Delay; Recovery						
111	Improved EMT models for IBRs, verification & parameterization		CE - EMT model with IBRs integrated, validation study						
112	Voltage regulation at Substation due to higher level PV on T&D		CE - Simulating behavior of LTCs & cap banks/regulators with higher level DERs; and informing smart inverter settings accordingly						
113	CVO (Conservative Voltage Optimization)/VVO (Volt-Var Optimization) goals using smart inverter functionality		CE - Understanding impact smart inverter settings can have on CVO/VVO goals (via voltage control functions) wrt AMI deployment (access to granular target grid voltage data)						
114	Testbed environments to first prove DERMS hardware & software, including M&V + comms requirements		CE - Develop testbed for prospective DERMS gateway controllers						

5
PRIORITIZED ISSUES TO SOLVE

The potential technologies that are marked **bold and blue** were identified as the top priorities.

Team's Overall Solutions Priority List

Issue 1: Alleviating transmission bottlenecks to allow better deliverability of renewables throughout the state, unbottle constrained resources, allow more hydro imports, and reduce congestion

Potential Technologies

a. **Energy storage for T&D services**
b. **Low-frequency AC transmission**
c. **HVDC systems and grid**
d. **Utilization and coordinated deployment of FACTS (STATCOMs, SVCs, Series)**
e. **Dynamic/ambient adjusted transmission line and cable ratings**
f. Dynamic, closed-loop voltage/reactive power control
g. **Improved operator situational awareness**
    i. **Wide-area monitoring**
    ii. **Decision support tools**
    iii. **Advanced EMS/DMS automation**
    iv. **Advanced contingency analysis**
h. **Dynamic power flow controllers**
i. Renewable energy sitting tools

Issue 2: Optimize utilization of existing transmission capacity and right of ways, circuit load factor/dynamic rating

Potential Technologies

a. **Transformer/cable/transmission line monitoring systems**
b. **Advanced sensor placement**
c. Advanced transmission/sub-transmission voltage regulation
d. **Dynamic line ratings/equipment ratings**
e. **Energy storage for grid services**
f. **Advanced high-temperature, low-sag conductors (HTLS). New composite conductors.**
g. **New compact tower designs (e.g. Bold)**
h. **Power flow controllers (e.g distributed FACTS, like Smart Wires)**
i. GIS utilization
j. **SF_6 monitoring/SF_6 alternatives**
k. **Modular solid-state transformers and other advanced grid control devices**

l. **Improve utilization factor of transmission lines (redirect flow to underutilized lines)**

Team's Priority List

Avangrid

Issue 1: Alleviating transmission bottlenecks to allow better deliverability of renewables though-out the state, unbottle constrained resources, allow more hydro imports, and reduce congestion

Technology categorization

a. **Energy storage for T&D services (1)**
b. **Low-frequency AC transmission (3)**
c. HVDC systems and grid
d. **Utilization and coordinated deployment of FACTS (STATCOMs, SVCs, Series) (2)**
e. **Dynamic/ambient adjusted transmission line and cable ratings (4)**
f. Dynamic, closed-loop voltage/reactive power control
g. Improved operator situational awareness
    i. Wide-area monitoring
    ii. Decision support tools
    iii. Advanced EMS/DMS automation
    iv. Advanced contingency analysis
h. Dynamic power flow controllers
i. Renewable energy sitting tools

Issue 2: Optimize utilization of existing transmission capacity and right of ways, circuit load factor/dynamic rating.

Technology categorization

a. Transformer/cable/transmission line monitoring systems
b. Advanced sensor placement
c. Advanced transmission/sub-transmission voltage regulation
d. **Dynamic line ratings/equipment ratings (4)**
e. **Energy storage for grid services (1)**
f. **Advanced high-temperature, low-sag conductors (HTLS). New composite conductors. (5)**
g. New compact tower designs (e.g. Bold)
h. Create a 765kV network (run 765kV designed lines at 765kV instead of 345kV)
i. **Power flow controllers (e.g distributed FACTS, like Smart Wires) (2)**
j. GIS utilization
k. SF_6 monitoring/ SF_6 alternatives
l. **Modular solid state transformers and other advanced grid control devices (3)**

m. **Improve utilization factor of transmission lines (redirect flow to underutilized lines) (2)**

NYISO

Issue 1: Alleviating transmission bottlenecks to allow better deliverability of renewables though-out the state, unbottle constrained resources, allow more hydro imports, and reduce congestion

Technology categorization

d. **Utilization and coordinated deployment of FACTS (STATCOMs, SVCs, Series)**
e. **Dynamic/ambient adjusted transmission line and cable ratings**
g. **Improved operator situational awareness**
   i. Wide-area monitoring
   ii. Decision support tools
   iii. **Advanced EMS/DMS automation**
   iv. **Advanced contingency analysis**
h. **Dynamic power flow controllers**

Issue 2: Optimize utilization of existing transmission capacity and right of ways, circuit load factor/dynamic rating.

Technology categorization

a. **Transformer/cable/transmission line monitoring systems**
d. **Dynamic line ratings/equipment ratings**
i. **Power flow controllers (e.g distributed FACTS, like Smart Wires)**
m. **Improve utilization factor of transmission lines (redirect flow to underutilized lines)**

NG

Issue 1: Alleviating transmission bottlenecks to allow better deliverability of renewables though-out the state, unbottle constrained resources, allow more hydro imports, and reduce congestion

Following Technology Categories were chosen–

a. **Dynamic/ambient adjusted transmission line and cable ratings**
b. **Improved operator situational awareness**
   i. **Advanced contingency analysis**
c. **Dynamic power flow controllers**

Issue 2: Optimize utilization of existing transmission capacity and right of ways, circuit load factor/dynamic rating

Following Technology Categories were chosen–

a. **Transformer/cable/transmission line monitoring systems**
b. **Dynamic line ratings/equipment ratings**

c. **Power flow controllers (e.g distributed FACTS, like Smart Wires)**
d. **SF_6 monitoring/SF_6 alternatives**

PSEG_LI

Issue 1: "Alleviating transmission bottlenecks to allow better deliverability of renewables though-out the state, unbottle constrained resources, allow more hydro imports, and reduce congestion",

Following Technology Categories were chosen–

- **Energy storage for T&D services**
- **HVDC systems and grid**
- **Dynamic/ambient adjusted transmission line and cable ratings**
- **Improved operator situational awareness**
  a. **Wide-area monitoring**
  b. **Decision support tools**
  c. **Advanced EMS/DMS automation (Highlight the concerns on communication)**
  d. **Advanced contingency analysis**
- **Dynamic power flow controllers**

Issue 2: "Optimize utilization of existing transmission capacity and right of ways, circuit load factor/dynamic rating",

Following Technology Categories were chosen–

- **Transformer/cable/transmission line monitoring systems**
- **Advanced sensor placement**
- **Dynamic line ratings/equipment ratings**
- **Energy storage for grid services**
- **Power flow controllers (e.g., distributed FACTS, like Smart Wires)**
- **SF_6 monitoring/SF_6 alternatives**

NYPA

Issue 1: Alleviating transmission bottlenecks to allow better deliverability of renewables though-out the state, unbottle constrained resources, allow more hydro imports, and reduce congestion

Technology categorization:

e. **Dynamic/ambient adjusted transmission line and cable ratings**
d. **Utilization and coordinated deployment of FACTS (STATCOMs, SVCs, Series)**
h. **Dynamic power flow controllers**
a. **Energy storage for T&D services**
g. **Improved operator situational awareness**
   i. **Wide-area monitoring**

ii. **Decision support tools**
iii. **Advanced EMS/DMS automation**
iv. **Advanced contingency analysis**

Issue 2: Optimize utilization of existing transmission capacity and right of ways, circuit load factor/dynamic rating.

Technology categorization:

d. **Dynamic line ratings/equipment ratings**
a. **Transformer/cable/transmission line monitoring systems**
i. **Power flow controllers (e.g distributed FACTS, like Smart Wires)**
f. **Advanced high-temperature, low-sag conductors (HTLS). New composite conductors.**
g. **New compact tower designs (e.g. Bold)**

Con Ed

Issue 1: Alleviating transmission bottlenecks to allow better deliverability of renewables thoughout the state, unbottle constrained resources, allow more hydro imports, and reduce congestion

Potential Technologies

j. **Energy storage for T&D services**
k. **Low-frequency AC transmission**
l. **HVDC systems and grid**
m. **Utilization and coordinated deployment of FACTS (STATCOMs, SVCs, Series)**
n. **Dynamic/ambient adjusted transmission line and cable ratings**
o. **Dynamic, closed-loop voltage/reactive power control**
p. **Improved operator situational awareness**
    i. **Wide-area monitoring**
    ii. **Decision support tools**
    iii. **Advanced EMS/DMS automation**
    iv. **Advanced contingency analysis**
q. **Dynamic power flow controllers**
r. **Renewable energy sitting tools**

Issue 2: Optimize utilization of existing transmission capacity and right of ways, circuit load factor/dynamic rating

Potential Technologies

n. **Transformer/cable/transmission line monitoring systems**
o. **Advanced sensor placement**
p. **Advanced transmission/sub-transmission voltage regulation**
q. **Dynamic line ratings/equipment ratings**
r. **Energy storage for grid services**

s. **Advanced high-temperature, low-sag conductors (HTLS). New composite conductors.**
t. **New compact tower designs (e.g. Bold)**
u. **Power flow controllers (e.g distributed FACTS, like Smart Wires)**
v. **GIS utilization**
w. **SF_6 monitoring/ SF_6 alternatives**
x. **Modular solid-state transformers and other advanced grid control devices**
y. **Improve utilization factor of transmission lines (redirect flow to underutilized lines)**

Team's Issues Priorities List

Item # - Issue

1. **17, 23, 26, 28, 66 - Alleviating transmission bottlenecks to allow better deliverability of renewables though-out the state, unbottle constrained resources, allow more hydro imports, and reduce congestion**
    - Central Hudson Energy Storage Study
    - Low Frequency AC Transmission Study
    - Balancing Phases in Medium Voltage Systems
    - Optimal Forecasting Solution for Overhead Line Operations
    - Project 1: Models and Methods for Assessing the Value of HVDC and MVDC Technologies in Modern Power Grids
    - Project 2: Advanced Modeling of Land-Based and Subsea HVDC/MVDC Transmission System
    - Enabling Extreme Real-Time Grid Integration of Solar Energy (ENERGISE)
    - 94 - Energy Storage and Distributed Generation
    - P94.015: Energy Storage Technology Assessment
    - P94.017: Distribution Energy Storage Integrated Products and Projects
    - PS94D: Transmission Energy Storage
    - P94.019: Transmission and Bulk Energy Storage Technologies and Products
    - P35.013: Overhead Line Ratings and Increased Power Flow
    - P35.014: High Temperature Operation of Overhead Lines
    - P35.015: Qualification, Selection and Maintenance of Advanced Conductors
    - P35.019: HVDC Lines
    - P36.008: HVDC Land and Submarine Cable Systems
    - Best Practices for Operation, Maintenance, and Refurbishment of FACTS Controllers (3002012870). Many FACTS installations are approaching or exceeding 30 years of service. Components are aging, and utilities must make repair/replace decisions. This report provides best utility practices for operation, maintenance, and life extension strategies for existing FACTS controllers.
    - P37.116: HVDC Converter Stations and Flexible Alternating Current Transmission System (FACTS) Devices

- 39.012: System Voltage and Reactive Power Management
- P39.012B: Strategies and Tools for Improved Volt/Var Control and Management
- P39.012C: Reactive Power Scheduling using Voltage Control Areas and Forecasting
- P39.011: Real-time Operations Situational Awareness
- Develop initial concepts on models for hybrid and multi-terminal HVDC systems
- Develop and refine HVDC planning guidelines and perform a case study to demonstrate how scoping studies can be performed for incorporating HVDC in transmission.
- 40.024: Advanced Power Flow Control, HVDC Planning, and Contingency Analysis Methods and Tools
- P40.024A: Advanced Power Flow and Contingency Analysis Methods and Tools
- P40.024B: HVDC Planning
- P40.024C: Power Flow Controller Integration – Optimal Use among Other Transmission Alternatives
- Smart Wires
- Decision-Support Software for Grid Operators
- Real-Time Transmission Optimization (PNNL)
- Distributed Power Flow Control (Smart Wire Grid)
- Renewable Energy Positioning System (University of Wisconsin)
- Dynamic Power Flow Controller

Technology categorization

a. **Energy storage for T&D services**
b. **Low-frequency AC transmission**
c. **HVDC systems and grid**
d. **Utilization and coordinated deployment of FACTS (STATCOMs, SVCs, Series)**
e. **Dynamic/ambient adjusted transmission line and cable ratings**
f. **Dynamic, closed-loop voltage/reactive power control**
g. **Improved operator situational awareness**
    i. **Wide-area monitoring**
    ii. **Decision support tools**
    iii. **Advanced EMS/DMS automation**
    iv. **Advanced contingency analysis**
h. **Dynamic power flow controllers**
i. **Renewable energy sitting tools**

2. **24, 25, 82, 18,19, 73 - Optimize utilization of existing transmission capacity and right of ways, circuit load factor/dynamic rating**
    - Real Time Analysis of Transformer Oil
    - Underground Cable Advanced Monitoring and Diagnostic System
    - Machine Learning Platform for Ratio Transformer Failure Predictions

- Project 19: Advanced Sensor Development
- Project 14: Enabling a High penetration of Distributed PV Through the Optimization of Sub-Transmission Voltage Regulation
- Project 6: Operational and Strategic Implementation of Dynamic Line Rating for Optimized Wind Energy Generation integration
- Project 1: Energy Storage Demonstrations - Validation and Operational Optimization
- Advanced Overhead Line Design
- Field Trial of Aluminum Conductor Composite Core Carbon-Fiber Core and Aluminum Conductor Steel Supported HS285 Ultra-High Strength Conductors
- Understanding Maximum Load Capabilities of Polymer Braced Post Insulators
- *Sulfur Hexafluoride (SF_6) Leak Sealing* (3002012840). Documents test plan and results of small-scale lab tests for sealing leaks from breaker/GIS components that are at ground potential (threaded fittings, bus-flanges, and porous wields on bus-work). Identifies promising materials and repair techniques for full-scale laboratory and controlled field testing.
- *Alternatives to Sulfur Hexafluoride (SF_6) for Gas Insulated Substations (GIS) and Lines (GIL)* (3002010200). The report provides a summary of recent industry developments and EPRI activities.
- P37.108: Gas Insulated Substations and Lines
- New Tower Designs
- New Composite Conductors
- Run the 765kV-designed Lines at 765kV
- Modular Solid State Transformers
- Power Flow Controller for Renewables

Technology categorization

z. Transformer/cable/transmission line monitoring systems
aa. Advanced sensor placement
bb. Advanced transmission/sub-transmission voltage regulation
cc. Dynamic line ratings/equipment ratings
dd. Energy storage for grid services
ee. Advanced high-temperature, low-sag conductors (HTLS). New composite conductors.
ff. New compact tower designs (e.g. Bold)
gg. Create a 765kV network (run 765kV designed lines at 765kV instead of 345kV)
hh. Power flow controllers (e.g distributed FACTS, like Smart Wires)
ii. GIS utilization
jj. SF_6 monitoring/SF_6 alternatives
kk. Modular solid state transformers and other advanced grid control devices
ll. Improve utilization factor of transmission lines (redirect flow to underutilized lines)

3. **6, 52, 53, 67, 71, 76, 94, 56, 65 - Fast transient phenomena and control system interactions inverter-based resources and other power electronics, not typically captured by regular modeling and analysis, dynamic 3 phase, 8760 hrs/yr models at distribution levels**
   - Control Equipment Performance Monitoring utilizing PMUs
   - Advanced Stability Controls
   - Advanced Modeling of Power System Dynamics Using Machine Learning
   - Model Translation Tool
   - Deep Learning Computing System for Grid Operations
   - Sub-Synchronous Oscillation Screening & Mitigation
   - Real-Time Interconnection Studies and Control of New York Offshore Wind
   - Project 9: DER Siting and Optimization Tool for California
   - Project 21: Control Theory
   - Project 27: Distribution System Decision Support Tools
   - Project 28: Development and Deployment of Multi-Scale Production Cost Models
   - Project 11: Rapid QSTS Simulations for High-Resolution Comprehensive Assessment of Distributed PV Impacts
   - Project 12: CyDER: A Cyber Physical Co-simulation Platform for Distributed Energy Resources in Smart Grids
   - Project 13: An Integrated Tool for Improving Grid Performance and Reliability of Combined Transmission-Distribution with High Solar Penetration
   - Project 15: Visualization and Analytics of Distribution Systems with Deep Penetration of Distributed Energy Resources (VADER)
   - Project 16: Stabilizing the Power System in 2035 and Beyond: Evolving from Grid-Following to Grid-Forming Distributed Inverter Controllers
   - Project 1: Market and Reliability Opportunities for Wind on the Bulk Power System
   - Project 2: WindView: An Open Platform for Wind Energy Forecast Visualization
   - Project 1: Open-Source High-Fidelity Aggregate Composite Load Models of Emerging Load Behaviors for Large-Scale Analysis
   - Project 3: Measurement-Based Hierarchical Framework for Time-Varying Stochastic Load Modeling
   - Project 4: Protection and Dynamic Modeling, Simulation, Analysis, and Visualization of Cascading Failures
   - Project 2: Suite of Open-Source Applications and Models for Advanced Synchrophasor Analysis
   - Project 3: HVDC and Load Modulation for Improved Dynamic Response Using Phasor Measurements
   - Synchrophasor Applications and Tools for Reliability and Asset Management
   - P94.018: Distribution Energy Storage Modeling for Planning and Operations
   - P94.020: Transmission and Bulk Energy Storage Modeling for Planning and Operations
   - P200.003: Operations and Control for Modern Distribution Systems

- Inverter-Based DER Dynamic Response Characterization for Protection, Planning, and Power Quality
- Modernizing Distribution Planning Using Automated Processes and Tools
- PS1A: PQ Analytics and Opportunities for Transmission and Distribution
- P1.001: PQ Issues and Solutions for Transmission and Distribution
- P1.002: PQ Benchmarking, Standards, and Advanced Applications
- PS1B: PQ Monitoring and Intelligent Data Applications
- P1.005: Advanced Applications for Monitoring Systems
- P39.015: Monitoring, Control, and Data Analysis including Synchrophasor Applications
- P39.015A: Advanced Monitoring, Control, and Data Analytics Including Synchrophasor Applications
- Develop, validate, benchmark, and refine static and dynamic models of system components such as HVDC and loads, including improving use of the composite load model and benchmarking of the VSC HVDC dynamic model that can be used in system planning studies.
- 40.016: Model Development, Validation, and Management
- P40.016A: Planning Study Model Development and Management
- 40.023: Special Planning Study Methods and Tools
- P40.023B: Transmission Harmonics Planning
- P40.023C: Transmission Transient Analysis
- PJ40.023D_Subsynchronous Oscillations
- P40.022: Risk-Based Analysis in Planning Processes
- PS173A: System Planning Methods, Tools, and Analytics with Emerging Technologies
- P173.003: Transmission planning tools and models for inverter based resources
- PS173B: System Operations Methods, Tools, and Analytics with Emerging Technologies
- P173.005: Operational Support Tools to Manage Variability and Uncertainty
- P173.012: Flexibility and Resource Adequacy Methods, Metrics and Tools for System Planning
- Stochastic Optimal Power Flow
- Global-Optimal Power Flow (G-OPF)
- EPIGRIDS Transmission System Models (University of Wisconsin)

Technology categorization

a. **Special studies methods and tools**
b. **Tools for more detailed and higher-fidelity power grid modeling (e.g. EMT models)**
c. **Harmonic modeling, analysis, planning, and real-time monitoring**
d. **Sub synchronous oscillation modeling, identification, mitigation**
e. **Improved power system modeling (loads, dynamic loads, inverter-based resources, distribution systems, HVDC, FACTS)**
f. **Advanced control system for stability, frequency, volt/var controls**

g. **Stochastic load/generation modeling – stochastic analysis tools**
h. **Synchrophasor applications for modeling and control**
i. **Improved system planning tools (quasi-static time evolution and analysis)**
j. **Optimal (stochastic) power flow tools**

4. **3, 4, 8, 13, 69, 91 - System operating reserve requirements in the presence of high-penetration of intermittent resources**
   - Development of a Extreme Wind Forecasting Tool
   - Advanced Solar and Load Forecasting (Phase 3)
   - Using NYS Mesonet Data For ISM-Based Renewable, Load, and Outage Forecasts
   - Project 1: Virtual Batteries
   - Project 4: Providing Ramping Service with Wind to Enhance Power System Operational Flexibility
   - Operating Reserve Determination
   - Forecasting Advanced Operating Reserve Requirements with High Variable Generation Penetration
   - Synthetic Reserves from Distributed Flexible Resources

Technology categorization

a. **Wind/Solar forecasting tools**
b. **Virtual batteries**
c. **Synthetic reserves from flexible DERs**
d. **Tools for accurate determination of operating reserves**

5. **29, 30, 31, 32, 33, 34, 89 - Reduced system inertia and frequency regulation issues**
   - Control Equipment Performance Monitoring utilizing PMUs
   - Control of Grid Interface Inverters for Distributed Power system Stabilization
   - Project 15: Grid Frequency Support from Distributed Inverter-Based Resources in Hawaii
   - Project 10: Frequency Response Assessment and Improvement of Three Major North American Interconnections due to high penetrations of Photovoltaic Generation
   - Project 5: Understanding the Role of Short-Term Energy Storage and Large Motor Loads for Active Power Controls by Wind Power
   - Project 4: Advanced Machine Learning for Synchrophasor Technology
   - PS161G: Telecommunications
   - P161.053: Wide Area Networks
   - P161.054: Field / Neighborhood Area Network
   - Frequency Response Methods and Tools
   - P173.011: Voltage and Frequency Performance
   - Frequency-Based Load Control Architecture

Technology categorization

a. **Utilization of fast monitoring systems, like synchrophasor systems and applications**
b. **Grid inertia monitoring systems**
c. **Grid frequency support from inverter-based resources – Synthetic inertia, AGC capability**
d. **Installation of energy storage (batteries, flywheels, small-scale pumped hydros) for frequency control**
e. **Oscillation damping controls**
f. **Frequency-based load control**
g. **Faster secondary frequency control (algorithms and actuators)**
h. **Deployment of wide-area communications networks and field area networks (fiber/wireless backbone)**

6. **15,45,109 – Relay Protection/coordination concerns for renewable**
   - NY State-Wide Area Protection Study
   - Impact of Renewables on System Protection (3002013634, 3002013635):
   - P173.009: Impact of Renewables on System Protection

Technology categorization:

a. **Impact of renewables on system protection**
b. **Wide utilization of differential protection schemes**
c. **Innovative protection schemes, like traveling wave protection**

7. **105/106 - Inverter settings/ usage**
   - Smart Inverter Setting Guide
   - Learning Smart Inverter Study
   - PS174B: Smart Inverters and Grid Supportive Technologies
   - P174.003: Smart Inverters and Grid Supportive Technologies

Technology categorization

a. **Smart inverters and grid supportive technologies**

- Project 4: Grid Modernization Laboratory Consortium Testing Network
- Project 5: Grid Services and Technologies Valuation Framework
- Project 6: Grid Sensing and Measurement Strategy
- Project 22: Multi-Scale Integration of Control Systems (EMS/DMS/BMS)
- Autonomous, Decentralized Grid Architecture
- Development of test beds for new technologies, like the AGILe lab, as basis for developing, experimenting, and testing new technologies.

6
POTENTIAL TECHNOLOGY SOLUTIONS

Dynamic Line Ratings and Improved Transmission Utilization

Increased Transmission Capacity Overview

Transmission lines ratings, and transmission capacity upgrade projects can have several key drivers. A utility seeks to sustain system reliability, maintain efficient operation practices, and meet transmission capability objectives such as:

- Marginally increase the load carrying capacity of a feeder to account for annual load growth
- Increase the transfer capability of an interconnection, an option of multiple supporting lines may be available
- Significantly increase the power import capability into a load pocket as new load centers (typically large industry) emerge within an area
- Increase the export capability of an area with surplus generation, particularly to facilitate the interconnection of renewables

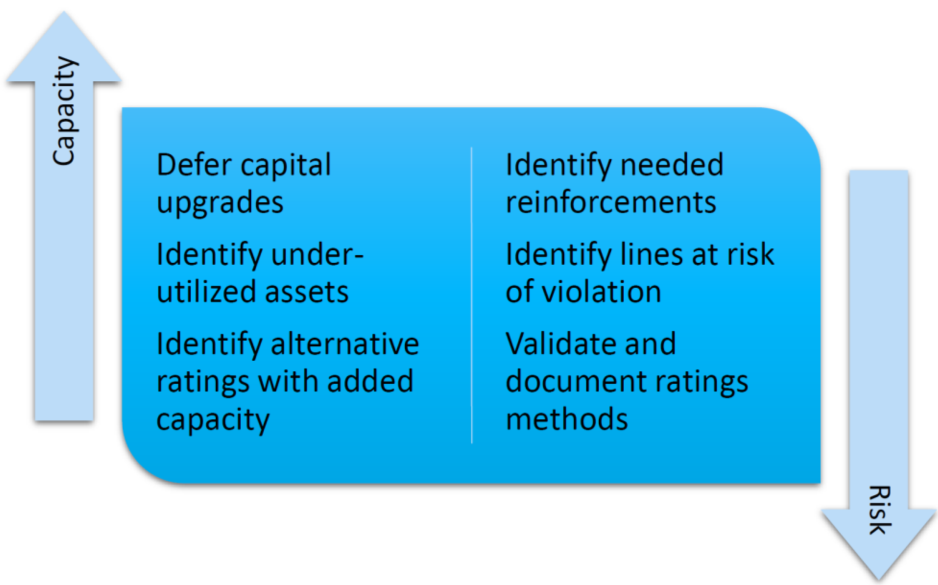


Figure 6-1
Optimization process to balance capacity and risks

Increase in capacity and increase in operational complexity typically go together. The more often a rating changes the more operators must do to accommodate the changes. In relative terms dynamic ratings give the highest capacity gains over other adjusted rating methods, see Figure 6-2. Of the dynamic rating approaches those that directly monitor the conductor may allow slightly higher capacity than weather-based ratings because the weather equations have necessarily built in conservatism to account for variables that are not typically measured or readily available.

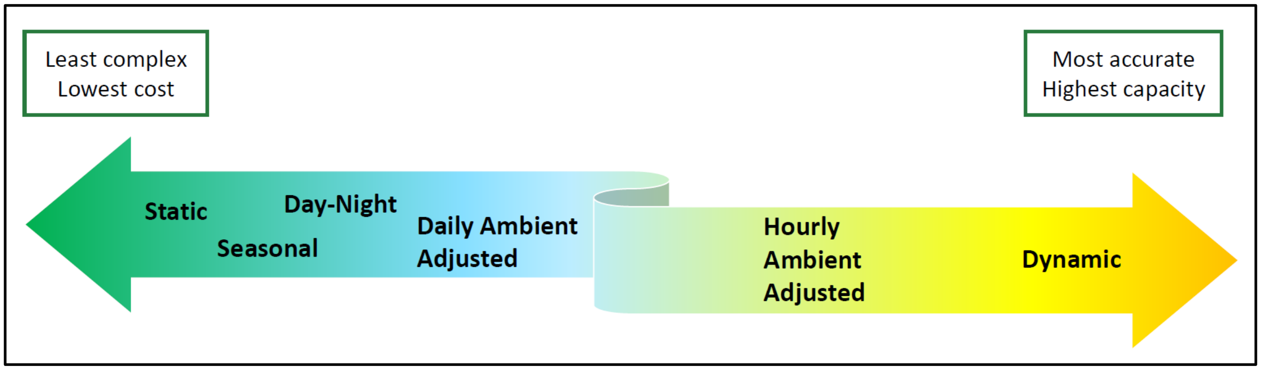


Figure 6-2
Relative capacity gains as compared to operational complexity

Understanding the Capacity Limits

The question may come to mind, "why can't we just send more power down the line?" The answer is that there are limits due to several factors. In most cases there is additional margin that can be utilized for a portion of the time even when a line appears to be up against existing limits.

Clearance Limits

As transmission lines carry power, they generate heat proportional to the electrical load on the line. The higher the electrical load, the hotter the lines become. As conductors heat, they expand, growing greater in length. This allows the conductors so sag closer to ground level or systems built under the lines (distribution lines, communication systems, pipelines, etc.). To maintain safe operation physical clearance limits are defined that limit how far transmission conductors are allowed to sag. By extension this determines how hot they can be, and therefore, how many amps can flow over the line before the clearance limit is reached.

Transmission line monitoring can allow utilities to have real-time intelligence regarding actual conductor positions as they change during operation. This further allows operation closer to the allowable limits. Traditionally, conservative margins must be maintained to assure reliability. Better knowledge of the line position allows more aggressive ratings to be used.

Thermal Limits

When a line has sufficient physical clearance, the next limit is a thermal limitation. When metals heat, they undergo changes in the microstructure which alters their physical properties. In the case of overhead lines, it can lead to a gradual weakening of the conductor, leading to mechanical failure of the line. The effect is most prominent on conductors where the aluminum strands carry mechanical load.

More modern conductors such as ACSS (aluminum conductor steel supporting) lines have a thermal limit associated with the corrosion protection systems. Above a certain temperature the protective system will degrade allowing the steel core (carrying the weight of the line) to corrode until it eventually mechanically fails.

The newest designs, such as composite core, are still thermally limited but at a much higher temperature level. The composite material in these conductors can be damaged above a thermal limit known as the glass transition temperature; as the damage accumulates the possibility of mechanical failure increases.

Like clearance limited lines monitoring can provided utilities with actual (or in some cases calculated) values of the conductor temperatures. Knowing the exact temperature allows the reduction of the conservative margins and operating closer to the design limit.

Next Limiting Element

When the limits of a transmission conductor are addressed it is critical to identify and consider the next limiting element. For example, if a conductor is capable of carrying a 20% increase in power flow, the associated line switches, breakers, CTs, bushings, transformers, etc. must be able to support the sustained additional load. In some studies, added transmission capacity can be realized through dynamic ratings but additional system reinforcements are needed to fully realize the potential power flow. [1]

EQUIPMENT	NAMEPLATE	NOR	LTE	STE
BUS 2A	3" AL, STL 230 KV	2015	2459	3244
CONNS	795 AAC	**876**	**968**	**1104**
DS 2615	1200 A	1260	1524	2160
BCT 1-2	2000 - 800/5	1200	1200	1600
CB 2614	1600 A	1664	1856	2128
BCT 3-4	2000 - 2000/5	3000	3000	4000

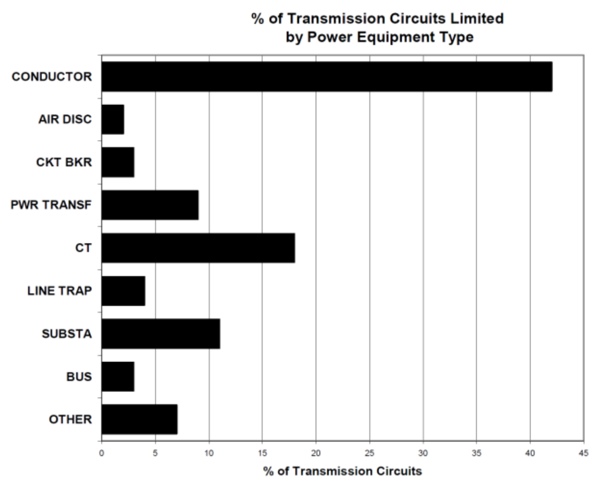


Figure 6-3
Comparison of conductors to next limiting elements

EPRI research has shown in most cases the conductor is the limiting element for power flow followed distantly by CTs (see Figure 6-3 right) when this is the case the capacity can be raised using DLR or AAR but the gains need to be capped to prevent damaged to the next limiting element. In the example shown in Figure 6-3 (left) the conductor capacity could be increased but not above 36% as that would overload the bushing CTs which are limited to 1200 amps.

This should not be taken as discouragement but a means to form an action plan. By strategically staging upgrades and focusing on future potential capacity, methods can be adopted that allow continuous improvements to the transmission system. While some upgrades may take several years to fully enact, staging upgrades strategically can reduce the overall time required to reach the initial return on investment. [2]

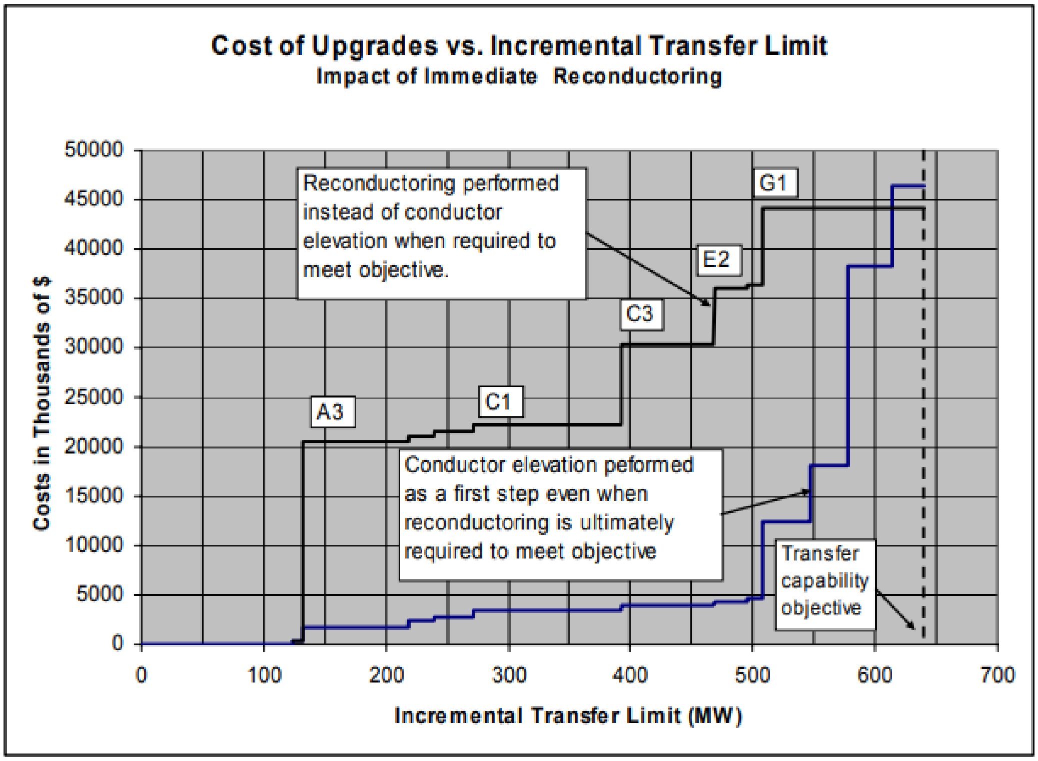


Figure 6-4
Example of spending approaches with incrementally performed upgrades

An advantage of uprating methods such as dynamic ratings is that the gains carry forward as a system is upgraded. For example, if a line has a dynamic ratings system added which allowed an increase in capacity, and later the line was upgraded with new conductors, the DLR tools will still give the same percentage increase over the final ratings allowed with the new conductors. [8]. This can also decrease the cost of the initial deployment of field monitors. A significant portion of the upfront cost is sending line crews to the necessary spans. When other work is being performed, the required personnel and equipment has already been mobilized. The relative cost of added time to perform the work is therefore much lower, and the utility can more efficiently gain benefits from multiple line upgrade solutions.

Changes in Approach Over Time

While other solutions exist for increasing capacity, many efficient solutions have been exhausted or are not feasible. For example, re-tensioning a line can be used to mitigate clearance concerns. However, the conductor, tower, and foundations must all be capable of supporting increased mechanical load for this to be a viable option. Increasing tension can also lead to vibration issues which are detrimental to conductor health if mitigation methods are not deployed.

Lines where it is practical to improve capacity using simple approaches are increasingly being upgraded leaving utilities wondering after re-conductoring, re-tensioning, or phase-raising what can be done next or where asset condition does not allow those approaches to be taken. Particularly in these cases alternative rating strategies such as DLR or AAR are attractive options. Similarly, if a line is already overloaded DLR tools may be able to realize enough capacity to reduce congestion while other reinforcements are planned and implemented.

Real-Time Ratings Technologies

Real time rating technologies seek to leverage the dynamic changes in the environment. Utilities using static ratings have more capacity available most of the time due to the conservative nature of the rating method. A static rating is simplest for design and operations as it never changes. The rating today is the same as the rating tomorrow. The odds of the true capacity of the line being lower than a static rating defines the rating risk. Ratings risk tolerance varies by utility and can vary within a utility transmission system. Case studies and available literature show that most utilities would have additional capacity available between 80 and 99% of the time. The amount of extra capacity depends on the real time weather conditions. [3]

For example, as shown in Figure 6-5, the real time rating changed over time. In this case the utility was observing a higher level of risk during nighttime hours (20% vs 10% as shown in the right-hand figure). Higher nighttime risks are typical for utilities using static, seasonal, or ambient adjusted ratings methods. In this case study the lowest rating periods were during two fall months. By switching from static ratings to a monthly rating scheme, the circuit's capacity could be kept available when most needed during peak summer loads. To accommodate the lower wind speeds during fall the rating would only need to be lower for two months, unless the utility determined the higher level of risk to be acceptable.

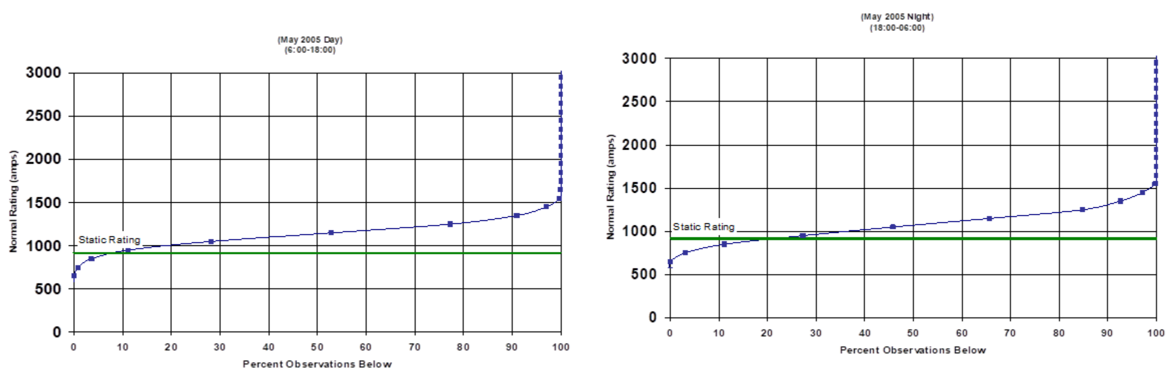


Figure 6-5
Comparison of real time ratings against static for daytime and nighttime averages

It is important to understand there are different levels of extra capacity at different times. Ratings that change with time seek to unlock the time periods when that extra power flow is available. For example, in the case study shown in Figure 6-6 the utility had less aggressive rating assumptions and the static rating was 3030 amps. This means there was an extra 10% of power flow available 90% of the time.

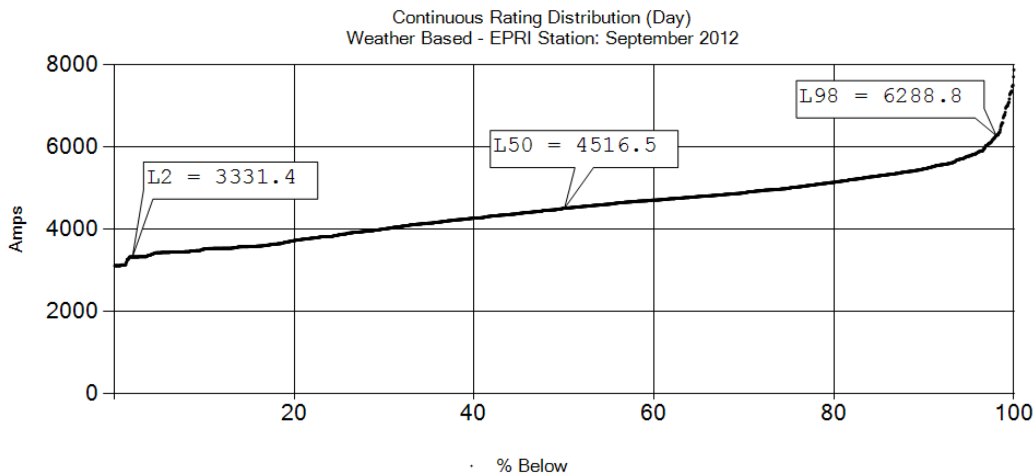


Figure 6-6
Statistical distribution of ratings changing with time- demonstrating continuous additional capacity

The available gain was at least 50% capacity 50% of the time. The smaller the capacity gain required the more often it is likely to be available. Knowing when this capacity is and is not available can be critical in maximizing transmission system throughput. Additionally, in some cases capacity is directly correlated to generation output.

In the case of wind farms, lines nearby experience high winds when the wind turbines do. As the power generation increases the amount of wind cooling for a line increases. As shown in Figure 6-7 the normal and emergency (LTE) ratings are typically increase proportionally to wind farm output. However, real time monitoring would still be required as winds are variable over distances and do not perfectly correlate to wind farm output. This is particularly the case when terrain can shelter and redirect winds. [4]

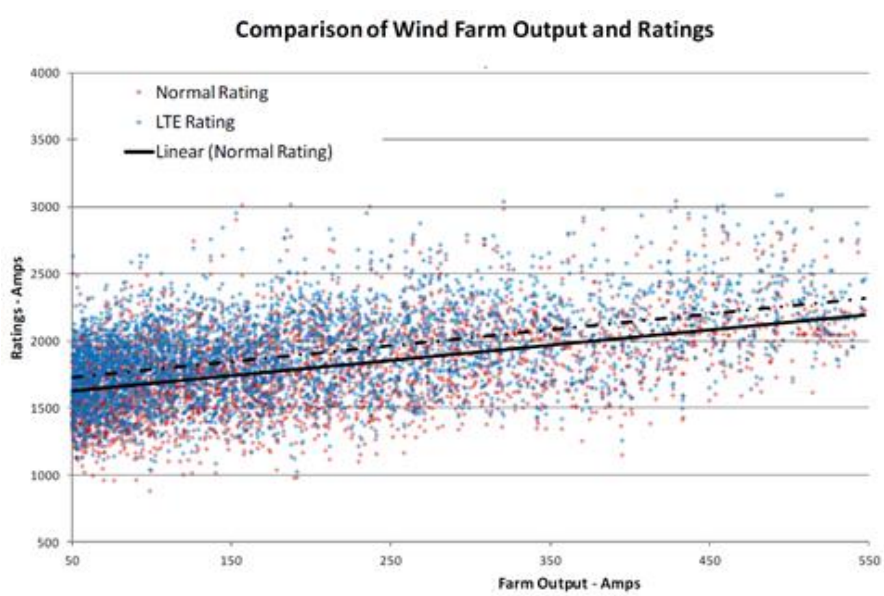


Figure 6-7
Example of highly correlated DLR and renewable generation capacity

This is also the case for solar generation. While the sun heats conductors, which is detrimental to line ratings, wind speeds are highest during midday. The increased wind cooling overcomes the solar heating which on average leads to a net increase in transmission capacity when generation is highest. Again, monitoring is required to ensure brief periods of calm wind or excessive air temperatures do not reduce the available capacity.

Application Considerations

While uprating methods for a single circuit may appear to have a lower impact on capacity than technologies such as reconductoring with advanced conductors, the economy of scale should be considered. For example, a weather station deployed in a right-of-way may increase throughput by 5%. In a corridor with two double circuit lines the increase will be 5% per span, or (assuming equal designs) a total increase of 20% capacity for the same life cycle cost.

Ambient Adjusted Ratings Considerations

Ambient Adjusted Ratings (AAR) carry higher risk of exceeding design limits as compared to Dynamic Line Ratings (DLR). With a simple AAR scheme, a wind speed is assumed and not measured in the field. The true capacity of the line is significantly influenced by changes in wind as demonstrated in Figure 6-8. An AAR does not capture the 12% increase in available capacity when the wind speeds increase from 2 feet/sec to 3 feet/sec. Alternatively, when using an assumed 2 feet/sec wind speed and not accounting for periods of low wind, lines could be operated over their thermal design limits, leading to significant conductor damage and potential clearance violations.

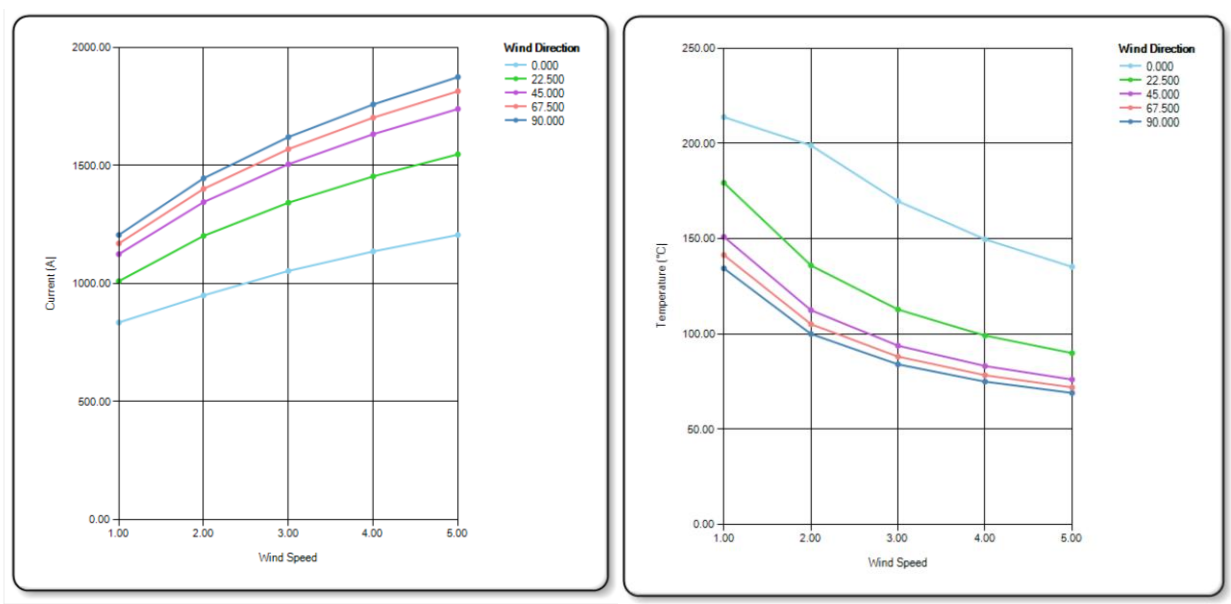


Figure 6-8
Comparison of rating and operating temperature as weather conditions vary

While a utility may assume the wind is a constant speed and direction leading to one rating, the true capacity of the line could vary significantly. Operating under an incorrect assumption can lead to lost capacity or risk of exceeding design limits depending on the actual conditions.

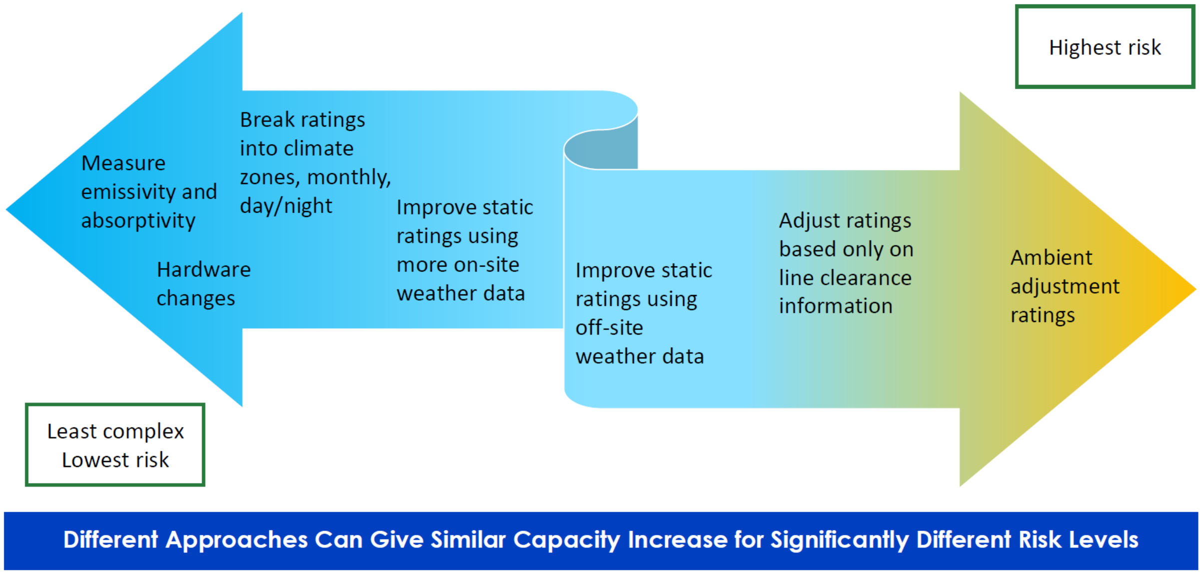


Figure 6-9
Comparison of risk for similar levels of capacity increase

Line Monitoring Considerations

When deploying new technologies special tools or practices may be required. It can be particularly beneficial to practice installations at ground level and at working heights to determine practices that will work best for a utility. Potential challenges from differences in work practices and familiarity with specific tools can be mitigated by gaining experience in a non-energized environment.

Figure 6-10
Utility line crew practicing installation of line ratings technologies at EPRI High Voltage Laboratory

Field Trials and Evaluation Testing

The growing industry need for tools that allow increased transmission capacity also is driving a growing industry need for independent testing. Line monitoring solutions, and vendors offering turn-key ratings analysis are changing constantly. There is a lack of long-term industry experience with any new tool or method sufficient to reduce risks of undertaking a wide scale deployment. To aid in the efficiency of field trials of new technologies it is beneficial for the industry to use similar terminology and methodologies, this will allow better direct comparison of the outcomes of different field trials. Without this focus, it will become difficult if not impossible to draw meaningful comparisons of regarding the effectiveness of different uprating solutions and significant duplicated efforts may be required to make appropriate decisions. A high-level overview of the methodology utilized by EPRI is shown in Figure 6-11.

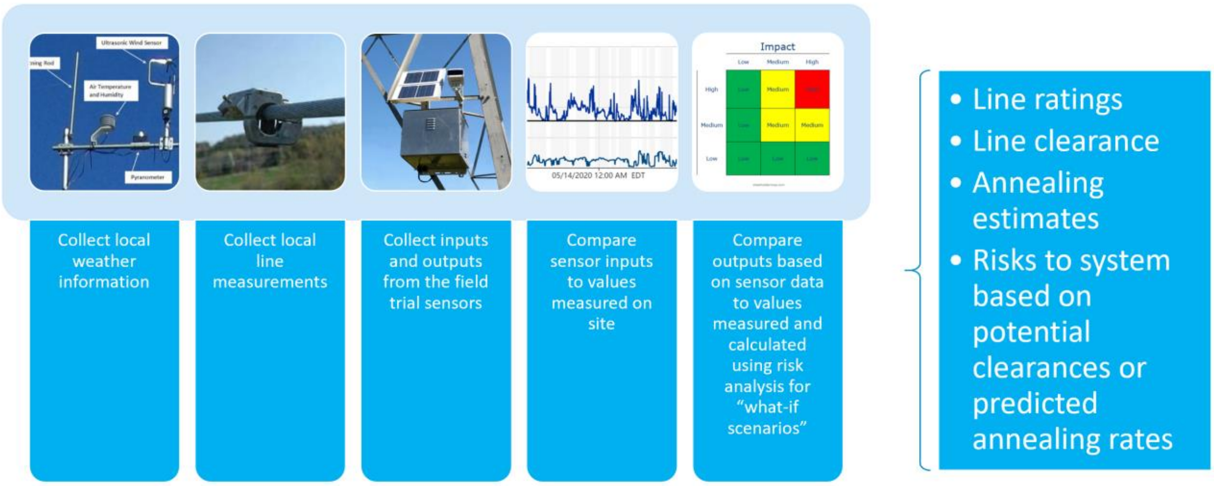


Figure 6-11
Field trial evaluation methodology

Field trials need to be of an appropriate duration to gather statistically significant findings. In some cases, vendors may propose shortened timelines to accommodate utilities requests, however, research indicates these shorter field trials can create significant increased risks to utilities as potential extremes in the data will not be represented. This may cause a loss of transmission capacity in some cases, but more commonly an increase in risks of overloading lines.

Historically field trials have focused on collecting weather data. Many projects have been completed by utilities independently, and in collaboration with research partners like EPRI. Some recent ratings projects have had key lessons learned summarized that focus on traditional ratings methods [10] and those that include more novel approaches. [11]

For various motivations, other on-line monitoring systems have been developed. These commercial solutions can lack the transparent methodology, industry guidelines, and proven history of weather-data based ratings. Given this, utilities are in need of independent research and assessment methodologies. It can also be challenging to derive the comparative, value, cost, life cycle performance, and risks of complex systems that interact with many different areas within a utility.

Reduction in Remedial Actions

In cases where capacity is required to alleviate remedial actions it may be possible to deploy an approach that does not require utilities to adopt the complexity of dynamic line ratings. In one field trial a utility used real-time weather data and conductor monitoring on a heavily loaded line. This line was the cause of a significant amount of remedial actions and load shedding despite being operated well above typical temperatures for ACSR. Wind sheltering in the area was light and the line section was short. By using real time weather and load data the utility was able to capitalize on the thermal inertia of the system and the fact additional capacity was available over 90% of the time based on real-time rating analysis.

The line was operated to the normal static rating levels, however, when the line would be overloaded in an N-1 state and remedial actions would be considered, the utility was able to look at “time-to-overload” calculations. The acronym for this is TTO. This approach uses the lower temperature a conductor has pre-contingency and considers how long it will take to reach design limits. In some instances when a remedial action was called for the time-to-overload could be seen to be greater than 4 hours. The utility could then wait while closely monitoring the situation. If winds picked up, or loads reduced, within the 4-hour time window then the remedial action could be deferred. In some cases, the overload would still occur, but the severity would require a less severe action. In this field trial, the occurrence and severity of remedial actions could be reduced by over 80% (several total hundred instances).

Readiness of Technology

A challenge the industry faces is keeping up with the pace of developments in monitoring technology. Some utilities have deployed a trial of a technology only to find the vendor has changed ownership or ceased operating. [4] In other cases a technology continues to mature and what is known about one version may not apply to later generations of the tool. [5]

To aid utilities in identifying if a technology meets their specific needs, an approach has been developed by EPRI to use a risk-based framework. A utility can use their tolerance for exceeding certain limits and their required capacity needs to define their risk-gain matrix. This is like the approach used to define emergency ratings: In rare circumstances higher levels of risk are tolerated to prevent system disruptions. A comparative study can be completed for each technology compared to a repeatable baseline of well understood measurement tools. This allows utilities to better understand the performance of a technology. This consistent method for testing is always applied for all technologies and rating methods.

For a utility to consider a technology for wide scale adoption it needs to meet three general criteria:

- The technology facilitates an increase in transmission throughput
- The technology is mature
- Use of the technology does not negatively impact the system (increase risk)

For a technology to be mature it needs to have been in use long enough for initial bugs inherent to the design or due to vendor inexperience to be resolved. Due to the limited use of real-time-ratings systems, vendors making gradual changes to their platforms, and lack of independent 3rd party testing, there is not enough information to specify the technology readiness level of AAR or DLR. Vendors with a long history are typically not seeing wide-scale utility adoption. [7] Of known technical publications and research performed it appears the readiness level would range depending on the tool from a 4 to a 6 in the classic TRL (Technology Readiness Level) scale; meaning the available products range from needing fundamental laboratory testing before field trials and being ready for a limited field trial deployment. The more mature technologies may be at the TRL 7 level indicating they are ready for field trials that include data ties to operational systems; however, this should follow proof of TRL level 6, completion of a scientifically based field trial.

Vendor Landscape

EPRI is continuously monitoring the industry for new technologies and observing the development of tools as they mature. A collection of information regarding real-time or near-real-time monitoring tools is maintained as periodic technical update [9]. A higher level of detail is provided on systems specific to line ratings and transmission capacity within the EPRI Increased Power Flow Guidebook [1] which is updated annually. The method of operation, known limitations, and noteworthy field trials are summarized in this guide. Currently over 20 technologies are represented.

These technologies will carry an initial cost, a maintenance cost, and a replacement cost at end of life. It will be important for utilities to consider the life cycle cost of these systems. Thoroughly documenting these costs can be challenging as utilities have indicated different prices for the same system. Considering system-wide monitoring tools with a greater coverage area may appear to be more cost effective to installing individual sensors. In some cases, this may serve only to increase system risks. The true capacity of any line is driven by the local weather conditions. Changes in geographic terrain, climate type, and the existence of microclimates will all limit the distance over which a rating can apply regardless of sensor accuracy and performance. The correlation of weather across a service area in conjunction with a utilities risk tolerance therefore determines how many sensors may be needed to effectively rate an entire transmission system, and the cost to properly site instrumentation for line ratings. [6] Line ratings technologies range from comparatively simple weather stations to research grade fiber-optic defractors or ground based Sodar stations. Regardless of the technology used, the true capacity of the line will vary with respect to local wind sheltering and the correlation of weather over distance. Technologies that do not account for both considerations will increase risks during operation.

Recommendations

Making changes from something that has historically worked can be a slow process. This is not necessarily a negative because a gradual adoption allows time for the industry to perform laboratory testing of new technologies, as well as field trials of more mature systems. It can be practical for utilities to establish, short, medium, and long-term goals. For example:

	Staged Deployment of Increased Power Flow Strategy
Within X years	Collect data and perform a risk based uprating study on majority of lines using field measurements and historical data
Within Y years	Deploy limited monitoring of critical spans Manage congestion with AAR, DLR, TTO, or on-line monitors
Within Z years	Expanded monitoring on “next most critical” spans Automated data integration

The primary recommendation, with consideration to the time required to perform accurate testing and to improve technologies, is that utilities develop a plan to assess their ratings to better understand what assumptions have been made, the accuracy of the data applied, and the baseline risk level of the present operating methods. This forms the technical basis for future work and cost-benefit analysis. Utilities may find they are inadvertently exposed to a high level of risk, in which case changing the rating method becomes urgent and cost justified. In other cases, a utility performing a risk assessment may identify additional capacity and determine where AA ratings or DLR would provide greatest benefit.

Regardless of methods or technologies considered, it is advised that utilities:

- Numerically (quantitatively) consider risks to the system when investigating new ratings methods or technologies
- Participate in collaborative research and share findings with the industry
- Utilize independent and scientifically justified approaches when comparing or qualifying new methods or technologies

It is recommended utilities consider improved ratings practices as not only a stand-alone process that can be used to overcome challenges, but also a component of the line design and operational processes that can work in concert with other technologies. The potential capacity an improved line rating can provide can influence line designs, asset maintenance, and replacement cycles, in addition to other areas.

The true capacity of a transmission line is a result of the overhead conductors selected, the local terrain, and the local climates. In most cases a utility will be collecting information for line ratings that has added value for other purposes. For example, collecting wind data to update wind and ice load calculations or collecting air temperatures to use in load forecasting models. When justifying the costs of a line ratings study or online monitoring equipment, utilities are encouraged to consider the additional benefits they can derive from the information they collect.

If a utility is unwilling to consider dynamic ratings or is in need of better risk-capacity optimization while working towards long term goals that will lead DLR, it is recommended utilities consider adopting a more complex ratings scheme. Many utilities use static or seasonal ratings. In this case their ratings will only change 1 to 4 times per year. A more optimal approach would be to leverage day-night ratings as well as monthly ratings changes. This would result in a table of 24 ratings for a specific circuit instead of 4. Day-night ratings better manage risks related to low overnight wind speeds and can capture increases in capacity during the day when wind speeds are higher. Monthly ratings changes reduce risks when going into adverse weather patterns and increase capacity more rapidly when conditions become favorable. To develop these ratings the most accurate results will be obtained when combining large amounts of historical data (over 15 years) as well as measurements directly within a utility right-of-way for at least a 1 year period.

Power Flow Control Devices – Distributed and Centralized FACTS

Introduction

Power flow control (PFC) devices, in addition to traditional transmission technologies, provide a suite of alternatives to more efficiently direct the flow of power on the grid, improving flexibility and enabling the grid to be more responsive and resilient. Traditional technology solutions to control power flow—such as phase-shifting transformers (PSTs)—have been used extensively for reducing loop flows or to maintain scheduled power flow on certain paths. They have also been used in some cases to reduce overloads by diverting power flow from heavily loaded lines to other lines with spare capacity, increasing the utilization of existing transmission assets and consequently reducing the need for certain transmission upgrades. In recent years, new power flow control (PFC) technologies have been developed. Relative to the more traditional power flow technologies such as PSTs, Flexible AC Transmission Systems (FACTS), and high voltage direct current (HVDC) technologies, the new PFC devices are simpler, more compact, and scalable. Some of these new PFCs have great potential but still are at an intermediate stage of development, while others are already commercially available, such as the distributed series compensator (DSC) technology, developed and commercialized by Smart Wires, Inc.

This section provides an overview of existing and emerging PFC technologies. It describes the main technical characteristics, application considerations, readiness of the technology, and vendor landscape. It also discusses considerations for the design and implementation of PFC-based solutions and barriers for wide-spread adoption of the technology. More detailed description of power flow controllers and application analysis can be found in: *Power Flow Control Integration: Technologies, Applications, and Solutions Desig*n. EPRI, Palo Alto, CA: 2018. 3002016163.

Power Flow Control Technologies

Power flow control (PFC) devices that operate in a meshed network can alter the natural power flow through the system by different means. PFCs can be classified based on different criteria. For example, the classification can be relative to the parameter of the transmission network that is mainly influenced by the device. Some PFC devices alter power flow by changing the impedance of the line where they are connected, while other devices alter the power flow by increasing or reducing the voltage phase angle applied across a transmission line in which they are connected.

A common way to classify PFF devices is based on the technology used. In this regard, PFC devices can be classified as:

- Electro-mechanical devices (PST, mechanically switched series reactors and capacitors)
- Power electronics based Flexible Alternating Current Transmission Systems (FACTS)
- Back-to-back HVDC: high voltage DC solutions

Electro-mechanical devices have typical switching speed of several seconds to minutes. They are widely used and well known within the power engineering industry and are very reliable and robust. FACTS devices are much faster. They can switch the full control range within a few periods of system frequency. Series connected FACTS such as TCSC and SSSC can change power flow in transmission lines, however they have been used mainly to improve dynamic stability and boost transmission capacity. Distributed Series Compensator (DSC) can be considered as new generation of FACTS devices, as they are power electronic-based controllers. DSC devices are specifically designed and used to control power flow in various conditions. They could also be used for dynamic stability improvement. Back-to-back HVDC systems provide large range of active power flow control while additionally decoupling the frequency of both sides. While thyristors-based back-to-back HVDC only controls active power, HVDC systems with voltage source converters allows full controllability of reactive power on both ends. This technology improves voltage control and stability together with the dynamic power flow control.

Table 6-1 presents an overview of the salient characteristics of each type of devices.

Table 6-1
Summary of power flow control technologies

Technology	TRL*	Type	Parameters influenced	Comments
Phase-shifting transformer (PST)	Mature. Many installations worldwide.	Electro-mechanical	Voltage angle across the line	Widely used in transmission system. Even though is a mechanically controlled device, the number of tap changer operations can be very high: 300,000 operations before maintenance Several vendors offer this technology
Series reactor	Mature	Fixed or Electro-mechanical	Line reactance	It does not provide great flexibility, but it may be a cost-effective solution in cases where smooth and frequent control is not a requirement.
Distributed Series Compensator (DSC)	Early commercial-ization deployment	Power electronic based FACTS	Line reactance (in SmartValve™ type, the injected series voltage can emulate impedance change)	Relatively new technology Several pilot demonstrations and a few commercial installations have been implemented. The salient characteristics are: modularity, "redeployability," and scalability
Series capacitors	Mature	Fixed or power electronic-based FACTS (TCSC)	Line reactance	Mainly used to boost line transfer capacity. About 16 TCSC installations worldwide. Most of them aimed to improve dynamic stability. TCSCs are not currently used for power flow control.
Unified Power Flow Controller (UPFC)	Relatively mature	Power electronic-based FACTS	Various: Bus voltage magnitude, voltage angle, active and reactive power flow	The most powerful and versatile FACTS device. Even though the first installation was in the 1990s, only five devices have been installed worldwide. Used for very specific applications where combined voltage control along with active and reactive power flow control is needed
Transformer-less Unified Power Flow Controller (TUPFC)	Demonstra-tion	Power electronic-based FACTS	Same as UPFC	New technology Currently available only for medium voltage level
Back-to-back HVDC	Mature	High voltage DC solutions		Mostly used to connect two asynchronous systems. Back-to-back systems can also be used to provide controlled power flow or increased transmission capacity. KEPCO in Korea plan to use this technology to mitigate overloads and limit fault current in the Seoul metropolitan area

*TRL: technology readiness level

Phase-Shifting Transformers

Phase-shifting transformers (PST) —or phase-angle regulators, as they are alternatively called—are relatively common in electric networks. They increase or reduce the voltage phase angle applied across a transmission line in which it has been located, thus controlling the amount of active power that can flow in the line. The basic principle to obtain a phase shift is to connect a segment of one phase into another phase. In practice, many solutions are possible to design a PST. The actual realization of a phase shifting transformer, however, opens a wide variety of options.

According to the IEC-IEEE Standard IEC 62032 2011 standard "Guide for the Application, Specification, and Testing of Phase-Shifting Transformers," PST types are classified as followed: asymmetrical, symmetrical, single-core and two-core. The last two types are also called direct (single-core) and indirect (two-core) respectively. A brief description of each type is provided next:

- Asymmetrical: In these PSTs voltage in quadrature with the line voltage is injected resulting in an increase of the magnitude of the output voltage. The resulting output voltage is shifted in phase with respect to the input voltage. The amount of the phase shift is controlled by a tap changer in the series winding. In asymmetrical PST, the output voltage is the phasor sum of both perpendicular voltages, and thus the magnitude of the output voltage is higher than the input voltage by a factor that depends on the inserted boost voltage. This causes a significant voltage rise in case of high phase shift angles.
- Symmetrical: In this case, under a no-load condition the voltage magnitude at the load side of the PST is equal to that of the source side. This is done by symmetrically inserting the voltage around a midpoint voltage. An on-load tap changers (OLTC) is used in the regulating windings to change the phase-shift angle under load. With this configuration, the same voltage magnitude for both ends of the phase-shifting transformer is achieved.
- Single-core**:** The PST is constructed with a single transformer. The advantage of the single-core design is simplicity and economy. The main disadvantage of this type of PSTs is that the short-circuit impedance can vary significantly from maximum to near zero for low tap changes positions. Also, the tap-changer is exposed to short-circuit currents and over-voltages in the system.
- Two-core or indirect-type PST configuration consists of a series unit and a main or exciter unit. Depending on the rating and maximum angle shift, the two-core PST can be built into one tank, or with two tanks for large ratings and high voltage PSTs. Indirect-type PST can be either symmetrical or asymmetrical.

In practice, many solutions are possible to design a PST. Usually, the manufacturer designs the device for each specific application considering all the requirements for the installation

PST Uses

There is large number of PSTs installed in many power systems around the world. They are extensively used in North America and Europe. A reference list of PSTs installations performed by ABB (2016 update) can be found in reference **Error! Reference source not found.**, while d etails of PST by Siemens are described in reference **Error! Reference source not found.**. A more detailed description of the use of PSTs in various transmission systems in Europe can be found in references **Error! Reference source not found.** to **Error! Reference source not fo und.**.

PST characteristics can vary from one project to another. Phase shift angle can range from a few degrees up to ±80°. Even though PST can be technically built for any voltage level, there are significant challenges with PST above 400kV. There is only one 500kV PST; the 525 kV PST at Sierra Nevada, installed by Salt River Project (Arizona) and Nevada Power Company (Nevada) **Error! Reference source not found.**. Regarding the purpose of PST installations, the main uses o f PSTs can be grouped as follows: a) reduce overloads at contingency conditions, b) force contractual/scheduled power flow over specific corridors at specified level (i.e.: tie lines with neighboring utility), c) mitigate loop or unscheduled flows.

PST Cost

Like in the case of large power transformers, the cost of a PST depends on several design parameters, such as: Rated MVA (throughput rated power), Max/min phase angle shift, PST type (number of cores, number of tanks, symmetric/asymmetric), Rate Voltage, Impedance, Characteristics of the on-load tap changers (number of taps, speed, capacity and duty of changeover selector), Overload capability, Efficiency, Sound level.

Typical costs for PSTs are not readily available in the literature or from utilities or vendors. EPRI obtained generic reference cost from Siemens Energy. According to Siemens experts, even though the investment cost depends on several factors, the parameters that primarily determine the cost of a PST are the MVA power rating, or throughput power, and maximum/minimum shift angle. Figure 6-12 shows the reference cost expressed as unit cost in $/MVA of MVA rating. It can be seen in this graph that the unit cost has significant variance across the MVA rating and phase angle ranges, varying from about $8,000/MVA for large units with low phase shift angles up to $72,000/MVA for smaller units with large phase shift angles. These numbers indicate that it could be inaccurate to evaluate PST project using general average value of unit cost.

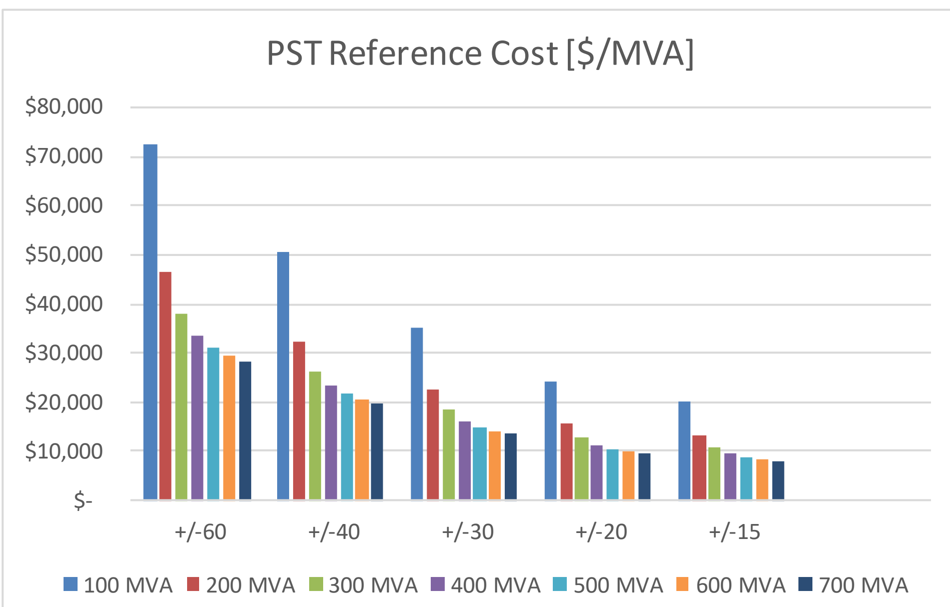


Figure 6-12

Per unit reference cost of PST as function of MVA rating and maximum shift angle (Created using cost data provided by Siemens)

PST Manufactures/Vendors

Even though PST is a very mature technology, PSTs are quite sophisticated piece of equipment. A small number of vendors worldwide manufacture these devices, being Siemens Energy and ABB the major ones. Below is a list of various transformer manufacturers that offer phase-shifting transformers:

- SIEMENS AG (Global):https://www.siemens.com/global/en/home/products/energy/high-voltage/transformers/phase-shifting-transformers.html
- ABB (Global)– More 95 units installed - http://new.abb.com/products/transformers/power
- TAMINI – (Italy) - http://www.tamini.it/product-focus/phase-shifting-transformers-pst
- TOSHIBA – (Japan) - http://www.toshiba-tds.com/tandd/products/trans/en/l_pstrans.htm
- Hyundai – (Kore/USA) -
- SGB-SMIT Group – (Netherlands) - https://www.sgb-smit.com/products/special-transformers/phase-shifters/
- CG Power and Industrial Solutions Ltd. (India) - http://www.cgglobal.com/frontend/Crompton.aspx?Id=a6+Ptuxdm38=
- Bharat Heavy Electricals Limited (India) - https://www.bhelbpl.co.in/bplweb_new/Default.aspx

Series Reactors

Reactors can be used in series with the transmission line to control the power flow through a modification of the transfer impedance. Series reactors are mainly used for two purposes, namely; limit short circuit current, or control power flow. In power flow control applications, series reactors can be used to mitigate overloads under contingency conditions, or to balance the power flow among different circuits in normal operations. In the first case, the reactor is shunted by a normally closed breaker that carries the line current under normal line loading conditions, and it is switched into the circuit only if a contingency occurs. Because of the relatively low cost, short lead times, and ease of transportation and installation, series reactors are attractive interim solution to mitigate short to medium-term power flow problems that are expected to be resolved by long-term permanent solutions such as new transmission line or major network reinforcement. The total time from project approval to energization could be less than 6 to 8 months **Error! Reference source not found.**.

A prototype of a controlled series reactor was developed as part of the TWENTIES project in Europe, which was an R&D project funded by the 7th Framework Program of the European Commission with the objective of increasing the wind power penetration in the European grid. The controlled series reactor developed by ABB, called Overload Line Controller or OLC, consists of three mechanically switched air-core reactors that are connected in series the line. This OLC is intended to provide an alternative solution for smooth power flow control using conventional series reactors, thus avoiding the cost and complexity of electronic-based power flow controllers. The functionality of the OLC has been tested and verified in field tests in the Red Electrica of Spain power grid. Nevertheless, no other installations have been reported.

Fixed and Variable Series Capacitors

Series compensation of high-voltage transmission lines is a common practice on relatively long lines. A series capacitor has a negative reactance that can subtract from the positive inductive reactance of a transmission line, thereby reducing the series reactance of this path. The result is that the line is electrically shortened, which improves angular stability, voltage stability and power sharing between parallel lines **Error! Reference source not found.**. Series capacitors m ay have limited control. Some series-capacitor banks are configured as one single module, and they are either in service or out of service—resulting in a two-step condition. Other series-capacitor banks on a transmission line may be composed of several modules that can be switched in and out in a greater number of steps. Series capacitors are used to increase transmission capacity and improve system stability. Therefore, even though series capacitors change the power flow pattern over the network, they are not usually intended to control power flow in the line.

A thyristor-controlled series capacitor (TCSC) is composed of a capacitor in series with the transmission line in parallel with a thyristor-controlled reactor (TCR) circuit. A metal-oxide varistor is also connected in parallel with the series capacitor and the TCR to protect the device against temporary overvoltage (See Figure 6-13). Variable capacitive and inductive reactance is achieved with controlled operation of the TCR. A TCSC module can be connected in series with a fixed series capacitor.

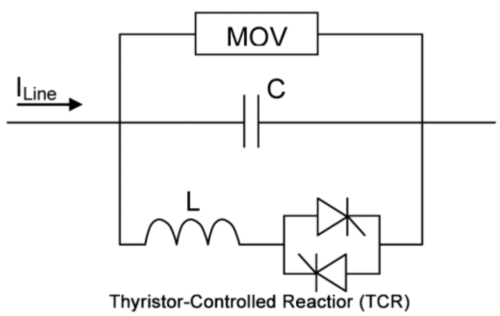


Figure 6-13
Single-line diagram depiction of a TCSC module

The TCSC technology was first demonstrated in the early 1990s in three locations in the United States. After that, several other projects have been carried out in various countries, including Brazil, China, Sweden, and India. The Cigre report 554 **Error! Reference source not found.** i dentifies fifteen TCSCs installed and in commercial operation worldwide. In most of the cases, the devices have been installed in long transmission corridors to damp electromechanical oscillations. One of the TCSC applications is solely for subsynchronous resonance control. TCSC has proven to be very robust and effective solution to improve damping of inter-area oscillation modes and thereby extending the possibilities for AC power interconnection between regions. More recently, Korea Electric Power Corporation planned to install two 345 kV TCSCs, each rated 500 Mvar, two support transmission system operation under N-2 contingency conditions. The compensators will enhance system dynamic stability following the loss of the primary 765 kV transmission corridor between east coast generation facilities and the Seoul load center. TCSC over fixed series capacitors were selected because their ability to improve transient stability and mitigate subsynchronous oscillations. Although a TSCS can control line power flow in steady state conditions, it is apparent that none of the exiting installations have been implemented for that purpose.

Distributed Series Compensation (DSC)

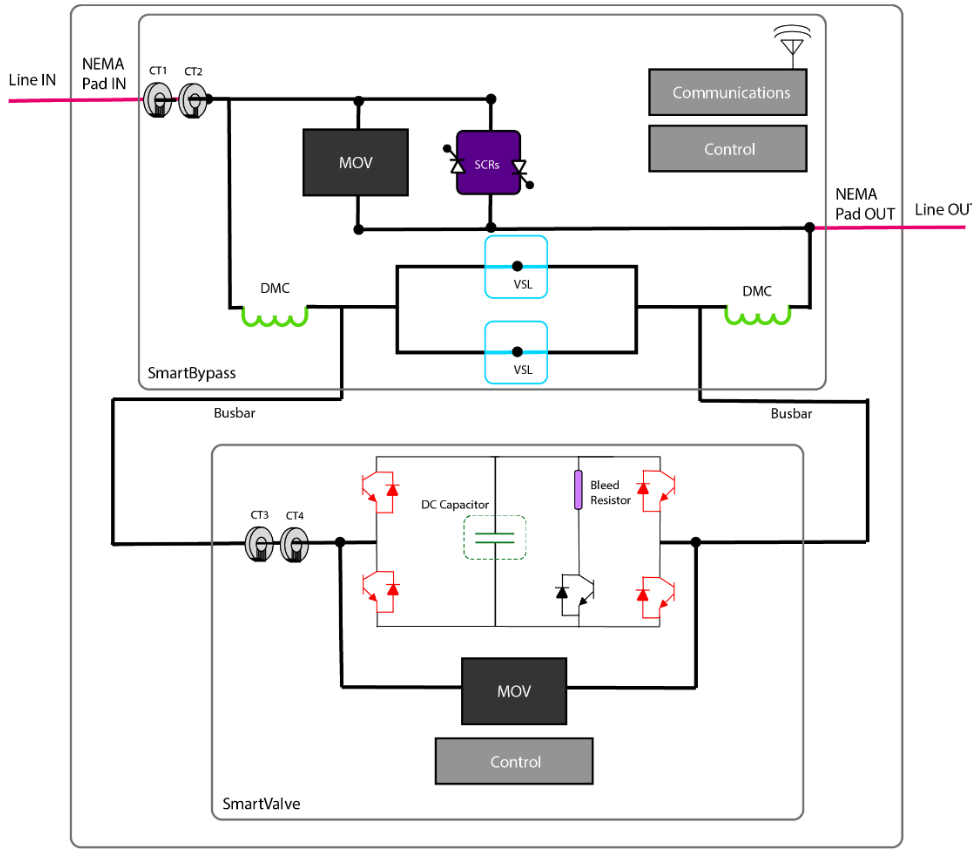
The first practical implementation of distributed series compensation was developed and demonstrated by Smart Wires Inc. under the auspice of ARPA-E's GENI program. Three other innovative power flow control technologies were also developed under that research program. This new hardware advancement was intended to more efficiently and cost-effectively direct the flow of power on the grid to reduce congestion, help minimize energy losses, increase network flexibility to better accommodate renewable generation, and enable the grid to be more responsive **Error! Reference source not found.**. The main idea behind the DSC concept is to p rovide a modular solution that can be quickly install and uninstall, allowing the solution to be scaled or moved as the needs of the grid change.

The first DSC devices were first introduced to the market in 2012, with Smart Wires Inc. launch of the PowerLine Guardian®. This product was a distributed, line-mounted, switched series reactor that uses magnetizing reactance to increase line impedance. The Smart Wires technology evolved significantly after the initial design. This section provides a brief overview of the newest devices. Details about the technology, including data sheet and description of current and future projects can be found in the Smart Wires Inc. website – www.smartwires.com.

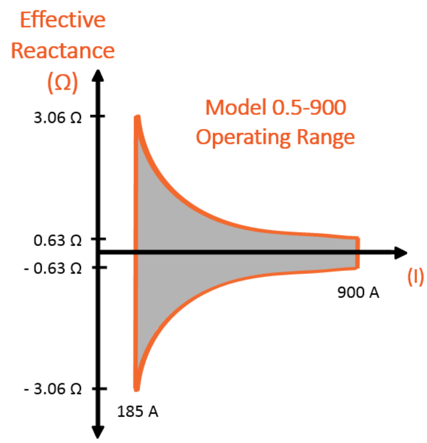
SmartValve™

The SmartValve™ is a modular Static Synchronous Series Compensator (M-SSSC). It works by injecting a leading or lagging voltage in quadrature with the line current, effectively increasing or decreasing the reactance of a given circuit. Hence this device can "push" power away from or "pull" power on to various lines to divert current from overloaded lines to underutilized circuits. The SmartValve provides similar functionality of a series capacitor or series reactor but does not have the negative characteristics of these passive devices such as the risk of sub-synchronous resonance with series capacitors. The SmartValve operates at line potential and has no connection to ground.

Figure 6-14(a) illustrates the basic electrical configuration of the SmartValve. The device acts as a solid-state synchronous voltage source, consisting of a voltage-sourced inverter as shown by the single-phase H-Bridge. The H-Bridge control circuitry measures the line current through CT3 (current sensor) and determines the magnitude of the voltage injected into the transmission line to maintain a desired reactance. Figure 6-14(b) shows the response of a 0.5 MVAr -rated SmartValve with a maximum continuous current rating of 900 A RMS and with a maximum output voltage of ±566 V RMS of the fundamental transmission line voltage. The figure plots the effective reactance injection as a function of line current. The orange boundary of the operating range represents the maximum reactance available as a function of line current, which is achieved when the voltage output injection is kept at a constant ±566 V RMS. The grey area inside reflects the feasible range of operation if the output voltage is varied lower than ±566 V.



(a)



(b)

Figure 6-14
SmartValve – (a) system diagram and (b) operating range (Source: [1])

Figure 6-15 shows a single-phase, SmartValve with a 0.5 MVAr rating. Typically, SmartValve units are installed across all three phases.

Figure 6-15
0.5 MVAr SmartValve [1]

A SmartValve deployment can operate in four possible control methods:

- Injection at a fixed voltage: The SmartValve fleet is set to output a fixed voltage injection that is either capacitive or inductive. In this control method, the injected reactance will vary as the line current changes.
- Injection at a fixed reactance: In this control method the SmartValve fleet is set to emulate a fixed reactance that is either capacitive or inductive. In this control method, the injected voltage will vary as the line current changes to keep the reactance at a set value.
- Current control: In this control method the SmartValve fleet actively regulates the magnitude of the current through the facility to stay below a given level or equal a given level.
- Set-point control: In this control method the SmartValve fleet is set to output a preset reactance or voltage. The operator may choose among various presets.

Reference Cost

Smart Wires provided EPRI the reference cost of SmartValve projects shown in Table 6-2. These costs represent total installed cost estimates (i.e. SmartValve devices plus related deployment costs). The table is broken into four increments based on the continuous current rating of the SmartValve solution. For example, the installed cost for a 60 MVAr solution comprised of 12 SmartValve 5-1800i devices would be $2.9M ($1.1 M + ($0.15M per device)*(12 devices)). These cost should be considered for reference only. The cost of an actual project may change considerably based on the project characteristics.

Table 6-2
Installation cost of SmartValve (Courtesy of Smart Wires Inc.)

			Components for Estimating Project Costs for Ground-Based SmartValve Projects[1]	
Device Model	Device Continuous Rating (A RMS)	Device Power Rating (MVAr)	Fixed Cost Component ($M per project)	Variable Cost Component ($M per device)
SmartValve 5-900i	900	5	$1.1	0.19
SmartValve 5-1800i	1800	5	$1.1	0.15
SmartValve 7.5-2700i	2700	7.5	$1.1	0.23
SmartValve 10-3600i	3600	10	$1.1	0.30

Distinctive Characteristics of DSC

The Smart Wires Distributed Series Compensator (DSC) devices have some distinctive operating and physical characteristics that open the possibility for new ways to solve challenging planning and operation issues in transmission systems. These features are:

a) Modularity and scalability: Unlike conventional expansion projects (new lines/substations, upgraded circuits, etc.) that are "lumped" solutions, a DSC installation is typically comprised of many devices or modules. That allows to deploy the solution gradually as the needs for transmission capacity expansion evolve over time, rather than installing all the devices at front as in the case of conventional expansion projects. If the system conditions change as compared to the conditions considered in the planning studies, the installation of the DSC devices can be halted, accelerated or modified accordingly.

b) Rapidly deployability: DSC can be installed in a relatively short time.

c) Redeployability: In many cases the devices can be relocated to other lines if they are no longer needed in the original location.

d) Steady state and dynamic control: The very fast control capability of these devices makes them applicable for both steady state power flow control (minutes time frame), and very fast dynamic applications. Because DSC are power electronic-based controllers there are no limitations in the number of control actions. Hence, they can be used to control power flow very frequently with no degradation of unit life. Control deadband can be set very tight improving the accuracy of the control action.

The main characteristics of DSC described above make this technology an attractive solution to achieve flexible expansion plans. Transmission expansion flexibility is an effective means to cope with the increasing uncertainties in the planning process. It expresses the ability of the system to change or react to unforeseen changes in system conditions with little penalty in time, effort, cost and performance. A more flexible expansion plan is one that can offer better adjustability for updating when demand level, generation pattern or other elements change **Error! Reference source not found.**.

Application Cases

PowerLine Guardian devices and some SmartValve have been installed in several utilities in North America, Europe, Australia. In most cases, those installations have been pilot projects to test and demonstrate the capability of the technology. Several commercial projects have been approved to be developed in 2020/21, or are already under construction. A list of projects is given below. Other technical papers and reports describing case studies and potential applications of DSCs can be found at the following link: http://www.smartwires.com/papers/.

- Pilot project with Eirgrid (Ireland): Completed in 2016: 3 SmartValve units tested
- UK Power Network: Sept. 2017 – May 2019: Trial of new technology to resolve network constraints between Bramford GSP and Lawford Grid 132kV substation.
- PowerLine Guardian to be installed on 132 kV circuit near Colchester: Pacific Gas and Electric Company. 90 PowerLine Guardian tested PG&E's Las Positas-Newark 230 kV line
- US: 7 of the 11 largest utilities are actively pursuing projects, 2 are customers with successful installations completed
- EUROPE: 2 of the 3 largest transmission organizations in Europe are customers and pursuing projects
- AUSTRALIA: Projects in progress with 3 of the 5 largest transmission players, including 2 recently approved by the Australian market operator
- Pilot installation of SmartValveTM and SmartBypassTM at Central Hudson 115 kV line. Details about this pilot project can be found in the following EPRI technical report: *Evaluation of Installation of SmartValveTM Devices at Central Hudson*. EPRI, Palo Alto, CA: 2020. 3002019771.

Unified Power Flow Controller (UPFC)

Conventional UPFC

The Unified Power Flow Controller (UPFC) is a generalized ac transmission controller that has multiple functional capabilities. The UPFC is a combination of a static compensator and static series compensation. It can act as a shunt compensating and a phase shifting device simultaneously. The UPFC consists of a shunt and a series transformer, which are connected through two voltage source converters with a common DC-capacitor, as schematically shown in Figure 6-16. The DC-circuit allows the active power exchange between shunt and series transformer to control the phase shift of the series voltage **Error! Reference source not found.**. T he UPFC is the most versatile power flow control device. It is able to independently and autonomously control voltage magnitude and active and reactive power flow.

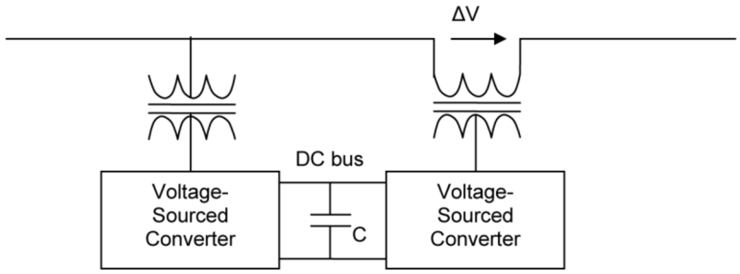


Figure 6-16
Single-line description of a UPFC

Even though its superior control capabilities, the UPFC has not being used widely in power systems. The first two installations were carried out in the USA in the late 1990s, the UPFC at the Inez Substation of American Electric Power (AEP) company, and the convertible static compensator (CSC) at the Marcy substation of the New York Power Authority (NYPA). The third UPFC application is in South Korea, at the Kang Jin substation. It was commissioned in 2003. These three UPFC use GTO-based converters. The other two installations are in China. One of them is the UPFC project Nanjing West Power Grid (NWPG) which was commissioned in 2015. This UPFC is the first using Modular Multilevel Converter (MMC) technology. The second UPFC in China was commissioned in December 2017. It is the world's first 500kV UPFC project. It is also the highest capacity, with three converters, each of them rated 250MVA. UPFCs are used in very specific applications where the need for combined dynamic control capability of active and reactive power is needed.

Transformer-Less Unified Power Flow Controller (TUPFC)

The transformer-less UPFC (TUPFC) is one of the four new power flow control technologies developed under the ARPA-E GENI program. The TUPFC consists of two cascade multilevel inverters (CMIs): series CMI and shunt CMI. The series CMI is directly connected in series with the transmission line, and the shunt CMI is directly connected in parallel to the line in the second terminal of the series CMI (See Figure 6-17 from **Error! Reference source not found.**).

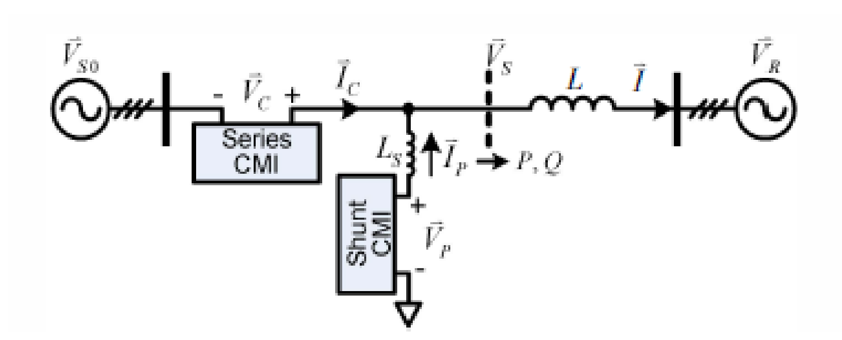


Figure 6-17
System configuration of transformer-less UPFC

Unlike the conventional UPFC, in this design no transformer is needed, no active power is exchanged between the two CMIs, and all DC capacitors are floating, which allows for a more compact, lower-cost, light-weight, and highly efficient device. It has the similar control capabilities to the UPFC.

The TUPFC was developed by Michigan State University (MSU). A pilot demonstration of a 13 kV TUPFC was performed at the MSU laboratory in 2015. More recently, Switched Source, a startup licensing the technology from MSU, has started projects with electrical utilities to deployed TUPFC solutions with focus on medium voltage distribution grids (up to 34.5 kV). A TUPFC demonstration project is planned to be deployed in Georgia Power's distribution system by the end 2018. The device will connect two 13.2kV feeders that operate normally open, so they cannot share their capacity. Connecting the end of the feeders through the TUPC will make it possible to increase the utilization of the existing feeders, reducing the need to upgrade them **Error! Reference source not found.**.

Back-to-Back HVDC

Back-to-back HVDC links provide connection between two ac buses within the same substation. Both ac/dc and dc/ac converters are located at the same HVDC station, and the dc circuit is only a few meters of busbar, normally inside the same building. They are used when the two ac buses have different frequencies or have the same frequency but are not synchronous. The back to back HVDC converters can be either based on traditional Line Commutated Converter (LCC) HVDC with thyristors or Voltage Source Converter (VSC) HVDC with IGBT switches. The merits of choosing either LCC or VSC HVDC are well established. EPRI's HVDC Planning Guide **Error! Reference source not found.** provides descriptions of both technologies and appropriate comparisons. There are many examples of LCC based back to back converters in North America.

Back-to-back systems can also be used to provide controlled power flow or increased transmission capacity. Some reasons for choosing a back to back converter for power flow control over other options may be that the back-to-back solves other grid issues at the location. For example, VSC HVDC can provide independent control over real and reactive power to provide voltage support at each ac terminal. They can also provide other benefits such as: a) ability to operate in low short circuit conditions, b) ability to quickly adjust real and reactive power in response to ac system contingencies, c) ability to operate in islanded conditions on one side of the back to back link, d) VSC converter station can be operated as two independent STATCOM devices should the need be required.

Considerations for Design and Implementation of PFC-Based Solutions

Selection of PFC Technology Type

The PFC technologies described above, in addition to traditional technologies, provide a suite of alternatives to more efficiently direct the flow of power on the grid, improving flexibility and enabling the grid to be more responsive and resilient. Even though all these devices are intended to improve the controllability of the transmission grid, they are very different from each other in terms of their physical and operational characteristics, underlying technology, operating principle, construction, costs, control capability, scalability, and applicability. Those characteristics will ultimately determine the viability and technical and economic convenience of using them for different applications in power systems.

In order to assess the feasibility and potential benefits of using PFC-based solutions is essential to understand how the characteristics of the different PFCs correlate with the requirements of each specific use case. Applications of PFCs include, but not limited to, loop flow control, congestion reduction, deferral of transmission expansion, overload mitigation, increased asset utilization, increased flexibility of system operations, and improved flexibility of transmission expansion. A more detailed guideline on how to select the right type pf PFC for different applications can be found in **Error! Reference source not found.**. A brief summary is presented i n the following table.

Table 6-3
Summary of potential PFC uses Error! Reference source not found.

Application	Requirements/ Applicable PFC technology	Criteria for selection of PFC technology	Most appropriate devices
Increased transmission capacity by reducing overloads	Potentially any PFC technology can be used depending on the requirement for the particular case	Selection based on technical merit and minimum investment cost criteria. The solution that complies with all the technical and performance requirements at the least cost possible would be preferred. For example, if a fixed series reactor is sufficient to solve the problem, it could the most cost-effective option.	Series reactor, PST, DSC, UPFC
Congestion reduction (due to thermal overload)	Static devices may be used for congestion conditions that do not change frequently. In cases where the congestion is discontinuous, controllable devices would be needed.	Selection based on economic convenience: positive benefit/cost ratio, and other economic metrics (payback period, internal rate of return, etc.) The technology that gives the highest benefit/cost ration, and complies with all other technical performance requirement, will be preferred. The potential benefit of implementing corrective control should assessed. The possible extra cost and complexity of implementing such control strategy will need to be considered in the economic evaluation.	PST, DSC, UPFC, Series reactor
Mitigation of unscheduled and loop flows	PFC devices that change phase angle, or back-to-back HVDC. Impedance-changed devices may not be effective.	PSTs are normally used for this purpose. The use of electronic-based PFC devices may be justified if fast control is needed.	PST, UPFC

Table 6-3 (continued)
Summary of potential PFC uses Error! Reference source not found.

Application	Requirements/ Applicable PFC technology	Criteria for selection of PFC technology	Most appropriate devices
Forced contractual flows	PFC devices that change phase angle, or back-to-back HVDC. Impedance-changed devices may not be effective to maintain power flows at target values	PSTs are normally used for this purpose. Electronic-based PFCs can provide more accurate control. Because they have continuous control capabilities and unlimited number of operations the control deadband can be set very small as compared with PSTs. The economic benefit of more refined control would need to compensate for the extra cost of more expensive technology.	PST, UPFC, HVDC
Mitigation solutions for maintenance and construction projects	PFC devices that can be quickly deployed and removed.	The cost and convenience to use temporary PFC solutions will be compared with other solution alternatives.	DSC, mobile DSC, series reactor, small PST
Flexible expansion solutions	Modular PFC devices, redeployable devices	The benefits of more flexible expansion plans will depend on the level of uncertainty on future conditions. PFCs devices would be combined with traditional projects	DSC, mobile DSC, series reactor, small PST

Benefits of PFC-Based Solutions

Some power flow controllers, mainly PSTs, have been extensively used in the electricity industry both domestically and internationally to solve specific transmission problems. Nevertheless, the full potential of PFC to improve transmission system efficiency and utilization is far from being realized.

Many studies conducted in actual power systems show the potential benefits of PFC technologies **Error! Reference source not found.**. EPRI, in study performed for the U.S. Department of E nergy, evaluated the costs and benefits of using flow control devices to reduce congestion or meet reliability standards **Error! Reference source not found.**. The study showed that placing 1 3 power flow control devices in the PJM system in optimal locations to reduce thermal overloads may reduce annual production cost savings by $67 million. Considering the initial investment cost of $137 million, the payback period is roughly 2 years. In the same study, EPRI looked at the SPP system and analyzed if flow control devices could defer transmission investments. In many cases these alternative technologies provided costs savings—for example, using two FACTS devices to remedy thermal overloads of an existing line would cost only between $1.5 million and $5.2 million, compared to installing a new 115 kV line at a cost of $16.8 million.

Smart Wires Inc. performed a study analyzing the potential benefits of modular FACTS devices (DSR) to support construction of new transmission lines. The study identified that the redispatch needed to avoid overloads during construction could be avoided by installing DSR devices and rerouting the flow from these otherwise overloaded lines. The estimated a net saving due to reduction in redispatch cost could range from $61.5 million to $69.7 million over the construction duration period of 3.5 years (depending on when the construction starts).

In a study conducted by EPRI and the Bonneville Power Administration (BPA) to identify and design power flow control solutions to mitigate overloads in the BPA's transmission network, PFC technologies were considered as potential alternative for relieving congestion along a major transmission corridor as opposed to building new transmission infrastructure. Various solution alternatives were evaluated. Among those alternatives, the most practical solution identified was one that combines three PSTs with one series reactor, and the upgrade of a critical 230kV line.

PFC technologies offer significant benefits by enhancing the capabilities of the existing grid. These alternative solutions are complementary to transmission expansion projects to enhance the capability and cost-effectiveness of the investments, like in the BPA study described above.

The salient characteristics of new PFC technologies, in particular modular and scalable devices such as DSR, make them effective options to improve expansion flexibility and adaptability of transmission networks. Even though transmission expansion projects will continue to be the backbone of grid development, the use of these advanced technologies allows planner to design highly adaptable and flexible transmission expansion plans which are critical to mitigate capital losses and reduce reliability risks associated with possible system future changes and unforeseen situations. Certainly, unlike conventional assets such as lines and substations that are lumped solutions in nature, these technologies can be gradually installed as they are needed, based on the evolution of system conditions. Furthermore, one far-reaching advantage of incorporating flexible assets in the planning process is the possibility to defer commitment to major conventional projects until the need for such investment is fully established. In other words, use as interim solutions until more information regarding system evolution is available, and definite solutions can be devised. Apart from the modularity and scalability features of these devices, they can be installed in a relatively short time and can be relocated to other part of the system if they are no longer needed in the original location (this feature is usually referred as "redeployability"). Those characteristics make the advanced technology solutions even more flexible and adaptable and will also enable faster response to emergency conditions. Besides, in some cases advanced transmission technologies can be suitable options in situations where new transmission lines cannot be built because of environmental issues, land use, or other type of restrictions.

Barriers for Large Scale Adoption and their Possible Solutions

As described above, many studies, pilot projects and actual deployment show that PFC technologies can be very beneficial, however they have been used on limited scale in North America. The slow pace of adoption may be driven by several factors:

- *Not wide-spread knowledge of the technology features and capability*: Even though some PFC technologies like PST have been used for a long time, not many planners are very familiar with the technical, operational, and economic characteristics of traditional and emerging PFC technologies. Therefore, it is necessary to develop reference material to help planner make risk-informed decision on the use of PFC technologies as a complement to traditional transmission expansion, by enabling higher utilization of the existing network infrastructure **Error! Reference source not found.**. Further investigation is needed to better understand and assess the full range of benefits that PFC technologies can provide.

- *Technical aspects*: There are many different possibilities to implement the control of PFC devices, depending upon the application, the type of device and its control capability, and the control performance expected for the PFC-based solution. In some applications, especially those designed to solve localized overloads, one or several devices with local control using locally available measurements can be implemented. In other applications a centralized control based on wide area measurements and remote control is needed for. Hence, in those cases, it is necessary to consider the communication infrastructure required for the implementation of the control system, which may represent a significant portion of the total cost of the solution. Other aspects to consider is the potential adverse interactions among various PFC when they are connected close to each other or their areas of influence overlap. In applications where corrective rather than preventive control is used it is necessary to consider the potential reliability implications in case of failure or malfunction. These aspects may hinder adoption of PFC-based solutions.
- *Lack of dedicated planning tools*: In order to take advantage of the features and capabilities of PFCs, planners need appropriate models, analytics methods and tools to design PFC-based solutions. as well as knowledge of operational practice and procedures to operate and control PFCs in an effective and reliable manner. The study of reference **Error! Reference source n ot found.** presents a methodology to locate PFC to reduce congestion in thermal limited transmission corridors. In a related effort, EPRI has developed a software tool – CPLANET - intended to help transmission planners identify the optimal location and size of power flow control devices for mitigating thermal overloads in a transmission system over a considered range of operating scenarios. .he optimum solution is determined from a given set of candidate projects that may include power flow controllers (Phase-shifting transformers, DSR, and fixed series reactors), energy storage, as well as traditional expansion projects like new and/or upgraded transmission lines and substations **Error! Reference source not f ound.** .
- *Lack of incentives and regulatory mechanism*: There is insufficient incentive for either the transmission operators or owners to use innovative technologies mainly because there are no rewards for enhancing operational efficiently. Performance of transmission systems operations is not measured strongly against improving operational efficiency, but rather focused on continuously meeting a minimum reliability threshold. In fact, innovating in operations could be considered as taking unnecessary risks.

  It is necessary to have in place proper regulatory mechanisms to ensure that the incentives are in place for entities to install PFCs. The entities that will own and operate these devices, especially for congestion management, must have clear instruments to receive the benefits that are given to the system to help pay for the capital costs of the system. Unlike a generator, which when installed in a system will earn revenue through the locational marginal prices, PFCs have no ongoing revenue stream from the benefits that they provide.

  There has been recent activity by US energy regulatory bodies in this regard. On March 20, 2020, the Federal Energy Regulatory Commission (FERC) issued a notice of proposed rulemaking in Docket No. RM20-10-000 to revise its regulations regarding transmission incentives for electric utilities. Among other incentives, FERC proposes to include up to 100-basis-point ROE incentive for transmission technologies that enhance reliability, efficiency and capacity, and improve the operation of new or existing transmission facilities. Examples of such technologies include advanced line rating management, transmission topology optimization and power flow control.

Energy Storage for T&D Services

Introduction

New York State, through its Climate Leadership and Community Protection Act ("CLCPA") has set a target that 70% of its electricity be produced from renewable resources by 2030 with the additional expressed goal of achieving a 100% carbon free grid by 2040. Included in the CLCPA targets is a 3,000 MW 2030 energy storage goal. This goal was preceded by a December 2018 New York Public Service Commission ("PSC") order establishing 1,500 MW target for 2025.

Energy storage is increasingly being considered for many transmission and distribution (T&D) grid applications to potentially enhance system reliability, support grid flexibility, defer capital projects, and ease the integration of variable renewable generation. Central to the state's policies and mandates is the need to enhance power system flexibility to effectively manage renewable energy deployment and the associated increase in variability. As power systems begin to integrate higher penetrations of variable, renewable, inverter-based generation in place of conventional fossil-fuel fired synchronous generation, grid-scale energy storage could become an increasingly important device that can help maintain the load-generation balance of the system and provide the flexibility needed on the T&D system.

Pumped hydro storage (PHS) and compressed air energy storage (CAES) are long-established bulk energy storage technologies. Utility-scale lithium ion battery storage has expanded dramatically, as decreasing lithium ion battery costs make this an increasingly cost-effective solution to meet T&D non-wire, reliability, and ancillary service needs. Redox flow batteries, sodium sulfur batteries, thermal energy storage (both latent and sensible heat), and adiabatic compressed air energy storage are all in various stages of demonstration.

This report provides a concise overview of a wide variety of existing and emerging energy storage technologies being considered for T&D systems. It describes the main technical characteristics, application considerations, readiness of the technology, and vendor landscape. It also discusses implementation and performance of different energy storage technologies. In this report, energy storage systems greater than 10 MW and four or more hours of duration, are considered as *bulk and transmission and sub-transmission-connected energy storage*. More detailed description can be found in the following reports:

- *Bulk and Transmission Connected Energy Storage: Technology, Deployments, and Lessons Learned: 2018 Update*. EPRI, Palo Alto, CA: 2019. 3002013722.
- *Energy Storage Technology Database Report*. EPRI, Palo Alto, CA: 2018. 3002013535.
- *Energy Storage Technology and Cost Assessment: Executive Summary*. EPRI, Palo Alto, CA: 2018. 3002013958.
- *Energy Storage Landscape*. EPRI, Palo Alto, CA: 2018. 3002013047.
- *Transmission Planning Considerations for Energy Storage*. EPRI, Palo Alto, CA: 2019. 3002016883.

Energy Storage Technologies Overview

This section provides brief overviews of many energy storage technologies, organized according to maturity. A wide range of T&D connected energy storage technologies are in various stages of development and demonstration. Figure 6-18, Table 6-4, and Figure 6-19 illustrates the energy storage technology categories, the form in which the energy is stored, benefits, challenges, applications, and the power and energy attributes. The key technology attributes commonly used to evaluate different technologies are based on life, footprint, cost, efficiency, response time, degradation implications, and safety. More extensive detail on many of these technologies is provided in EPRI's *Energy Storage Technology Database. Energystorage.epri.com*.

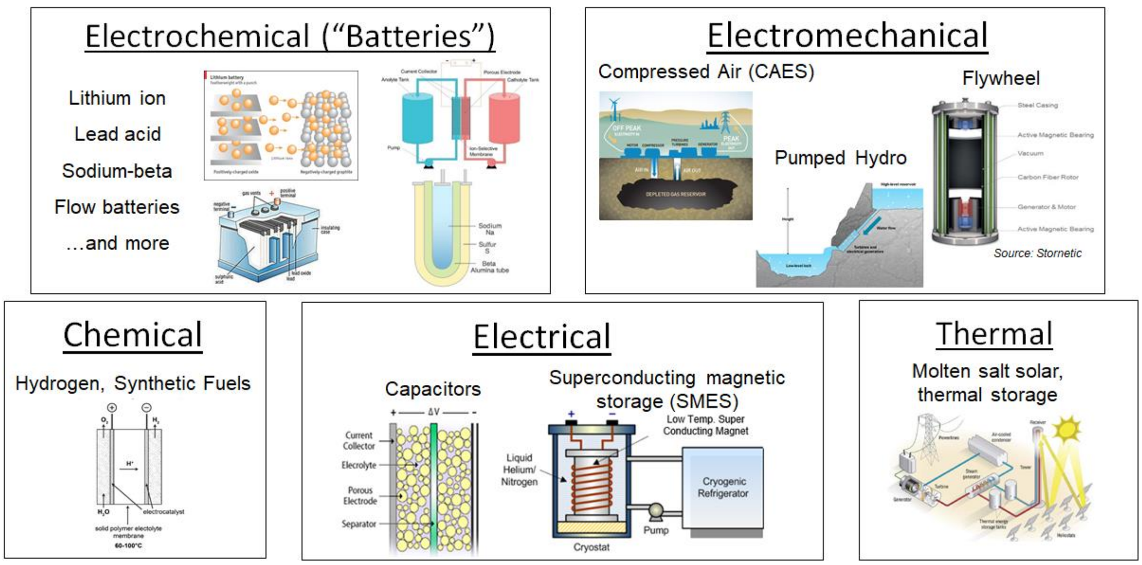


Figure 6-18
Energy storage technologies

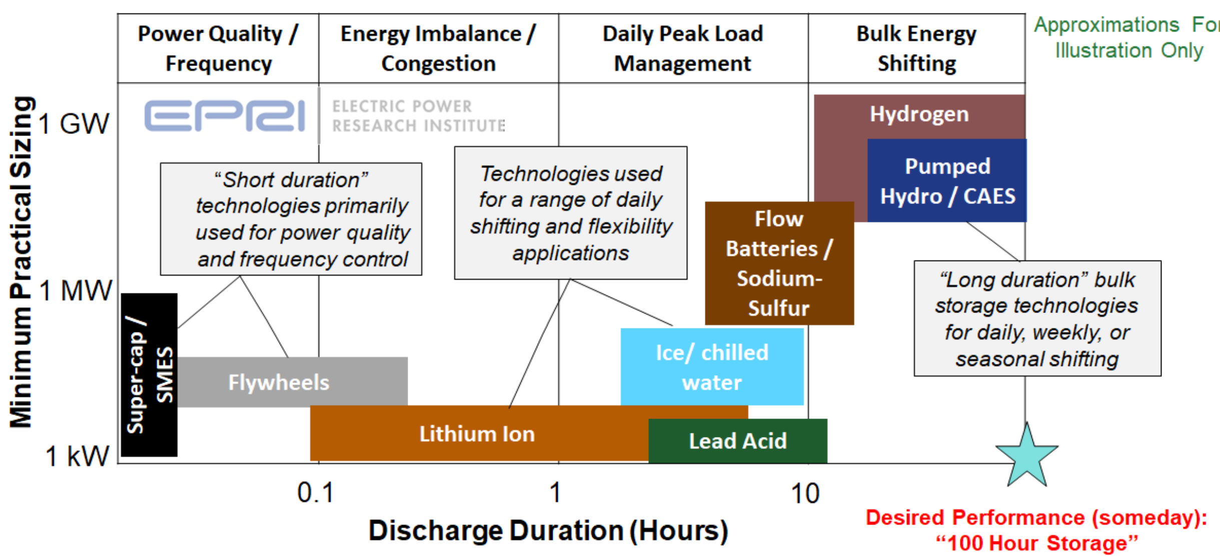


Figure 6-19
Energy storage technology attributes

Table 6-4
Energy Storage Technologies overview, benefits, and challenges

	Technology	Description	Efficiency	Benefits	Challenges
Mechanical	Pumped hydro storage	Water is pumped uphill to a holding pool to store potential energy. Electricity is generated as water is released through a turbine generator.	75-85%	▪ Reliable bulk storage	▪ Geographical limits ▪ Capital intensive
Mechanical	Compressed Air Energy Storage (CAES)	Air is compressed and stored in a cavern or other containment vessel. Electricity is generated as air is expanded through a turbine generator, often combined with natural gas combustion.	27-54%	▪ Reliable bulk storage	▪ Geological limits
Mechanical	Flywheels	The angular momentum of a spinning rotor is stored as kinetic energy inside a vacuum chamber. Electricity is generated as kinetic energy is released. Cycle life > 100,000, well suited for short duration applications.	80-90%	▪ Fast response ▪ High power	▪ Expensive ▪ Low energy density ▪ High self-discharge rates
Electrochemical	Batteries	Electrical energy is transformed into chemical energy through redox reactions. Electricity is generated when the reaction is reversed.	60-90%		
Electrochemical	▪ Lead acid	Charge is transferred between a lead oxide positive electrode and a lead metal negative electrode. Limited cycle life of ~1,000, well suited for off-grid applications and durations of 4+ hours.	50-90%	▪ Established technology ▪ Inexpensive	▪ Low energy and power density ▪ Environmental impacts ▪ Depth of discharge constraints
Electrochemical	▪ Advanced lead acid	Carbon doping of the electrodes for a more durable and efficient battery than traditional lead acid. Some technologies can offer cycle life of 5,000.	75-90%	▪ Inexpensive ▪ More Robust	▪ Low energy and power density
Electrochemical	▪ Sodium sulfur (NaS)	Sodium ions move across a membrane between a molten sodium negative electrode and a sulfur positive electrode. Cycle life of 2500-4,500, well suited for 6 hour durations.	85-90%	▪ High energy density ▪ Cost competitive with li-ion in 4+ hr applications	▪ High temperature required ▪ Limited power capabilities
Electrochemical	▪ Lithium ion	Lithium ions flow between a lithium metal oxide cathode and a carbon-based anode. Leading technology for <4-hour durations.	75-90%	▪ Good energy and power density	▪ Cycle life constraints ▪ Safety concerns
Electrochemical	▪ Flow batteries	Activated liquid electrolytes flow through a reaction cell and transfer electrons through a membrane. Cycle life reaching 10,000-12,000, well suited for 4+ hour durations.	65-80%	▪ Decoupled power and energy ▪ Improved cycle life	▪ Low energy density ▪ Added component with pumping
Electrical	Ultracapacitors	Electric charge is physically stored at the surface-electrolyte interface of high-surface-area carbon electrodes. Cycle life of over 1 million, suitable for short duration applications (<2 min).	70-80%	▪ Fast response times ▪ High power density	▪ Short duration ▪ Expensive
Electrical	Superconducting Magnetic Energy Storage (SMES)	Energy is stored in the magnetic field produced by the flow of direct current in a superconducting coil that has been cryogenically cooled to below its superconducting temperature.	85-95%	▪ Fast response times ▪ High power density ▪ High efficiency	▪ Short duration ▪ Expensive

Pumped Hydro Storage (PHS)

Pumped hydroelectric storage (Figure 6-20) is the most mature and widespread energy storage technology used for bulk energy storage at the utility scale. The input energy is used to pump water from a reservoir at low elevation to another reservoir at higher elevation. The water is run beck down through hydroelectric turbines to regenerate electricity. Pumped hydro systems are usually built as very large systems, delivering thousands of MW for several hours. As such, they are more suitable for applications at the transmission level than at the distribution level. The United States currently has just over 20 GW of PHS capacity in about 150 facilities across the country [1]. Worldwide, installed pumped hydro capacity is over 150 GW [2]. PHS facilities are most cost-effective at capacities over 1000 MW, and PHS facilities of this size have capital costs of $2,500—$4,000/kW [3]. Although there is continuing interest in PHS development in the U.S., environmental impacts and project permitting challenges have restricted development, with almost no new installations since 2000.1 (However, six PHS facilities have increased their reported nameplate capacity since 1995 [1]. These upgrades totaled 1,326 MW, and account for 6% of current U.S. PHS capacity.) As of late 2016, two proposed projects held FERC license authorizations. In addition, 36 other projects were at earlier stages of development. [4]

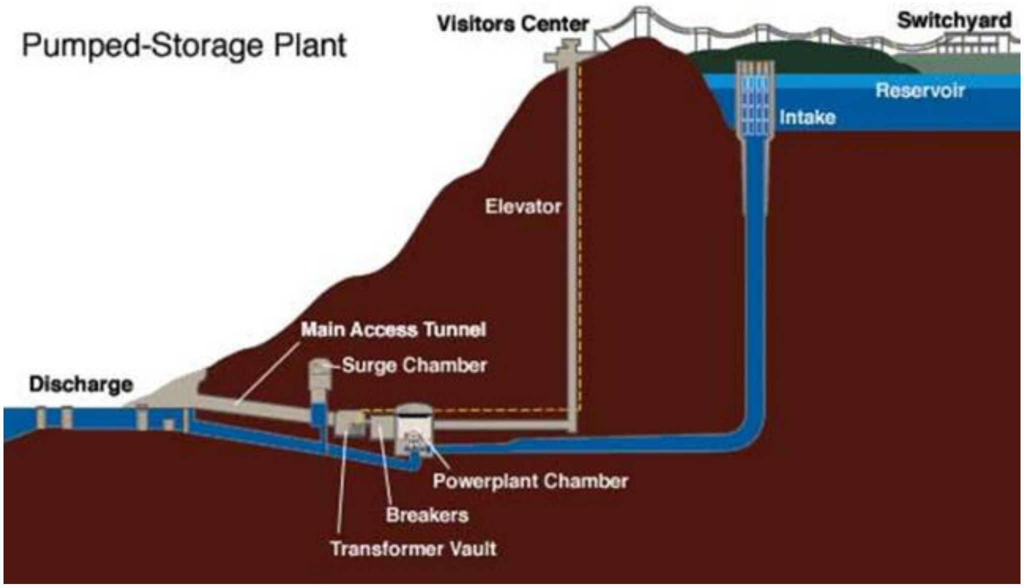


Figure 6-20
Pumped hydroelectric storage

Compressed Air Energy Storage (CAES)

As illustrated in Figure 6-21, compressed air energy storage (CAES) involves using electrical energy to compress air, store the air in a pressurized reservoir, and use the compressed air to generate electricity by heating it and passing it through an expansion turbine. The heat input is often delivered through the combustion of natural gas; in this case, the CAES system can be considered a simple-cycle combustion turbine with a separation between the compressor and expander, allowing both to operate independently and at separate times. CAES systems are usually designed on large scales, with power ratings in the 100s of MW and the capability to deliver that power for several hours. Typically, large underground caverns or aquifers are used to store the compressed air for these systems. An extended discussion of CAES technology is provided in a previous bulk storage technology report [8]. Two CAES facilities have been built, one in Germany (321MW 2hr) and one in Alabama (110MW 26hr). Both existing facilities use underground caverns to store the compressed air. Both have over 100 MW of charging and discharging capacity and have demonstrated decades of satisfactory performance [9]. Such systems are designed for load shifting at the transmission level; many are now proposed with wind projects for use in transmission curtailment reduction, time shifting. Five additional CAES projects in U.S. are in various stages of planning.

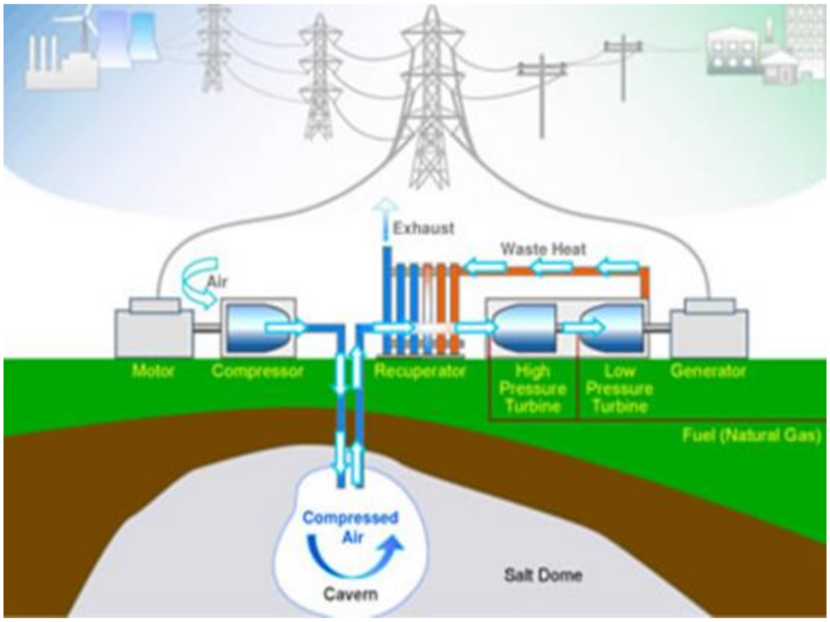


Figure 6-21
Compressed air energy storage

Lead-Acid Batteries

Lead-acid batteries are the oldest and most mature form of rechargeable electrochemical battery. Electrochemical batteries store energy in chemical form, by using input electricity to convert active materials in the two electrodes into higher energy states. The stored energy can then be converted back into electricity for discharge later.

Lead-acid batteries use lead electrodes in sulfuric acid electrolyte. They have been in commercial use for well over a century, in applications in every area of the industrial economy. Because of their low cost and ready availability, lead-acid batteries have come to be accepted as the default choice for energy storage in new applications. This popularity comes despite many perceived disadvantages, including low specific energy and specific power, short cycle life, high maintenance requirements, and environmental hazards associated with lead and sulfuric acid. Continuous improvements in chemistry, mechanical and electrical design, and operational and manufacturing techniques have mitigated many of these disadvantages, and lead-acid remains the most popular energy storage technology for large-scale applications.

Lead-acid batteries are categorized in several ways: method of electrolyte management (flooded vs. valve-regulated), grid alloys (lead-antimony vs. lead-calcium), application (cranking vs. deep-cycle). The performance can vary greatly between different types, and it is important to get the correct type of battery for a given application.

A number of distribution-level projects have been built from lead-acid systems. The best known was a 40 MW plant built in Chino, CA by Southern California Edison in the early 90s. The plant was designed to explore the use of energy storage in a number of applications, including load shifting for T&D deferral, frequency regulation, and voltage support. The Chino plant was preceded by several smaller scale projects and was followed by the even larger PREPA system at Sabano Llano, Puerto Rico. While most of the lead-acid battery systems were considered technical and economic successes, but the initial expense of such plants, their uncertain regulatory status, and the general antipathy of the utility towards lead-acid batteries resulted in limited follow-up to these projects.

Lithium Ion Batteries

Lithium ion batteries are a mature technology, with widespread commercial deployment, a large ecosystem of battery suppliers and system integrators, and warranties available. Figure 6-22 shows the extent to which lithium ion has been deployed since 2013 relative to other energy storage technologies.

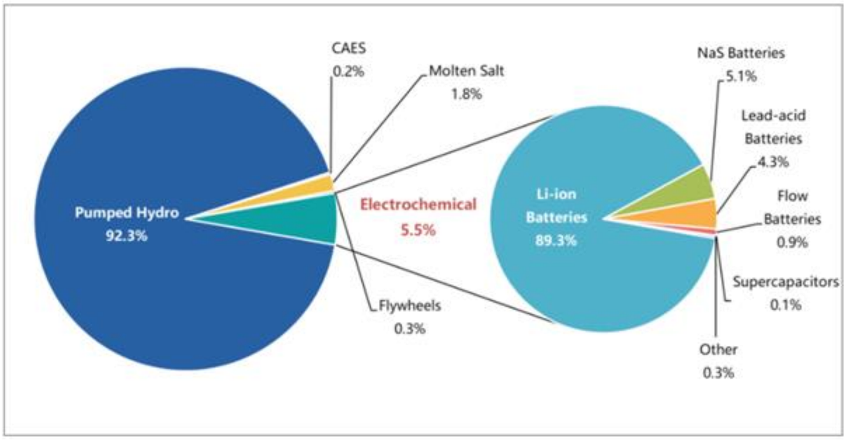


Figure 6-22
Global total operational energy storage project capacity (MW) (Source: http://en.cnesa.org/latest-news)

Lithium ion currently dominates battery storage deployments with more than 97% of the capacity of stationary ESS installations in the United States in 2017 [10]. Given current and projected costs, lithium ion is likely to remain in the leading position for most stationary applications for the at least the next five to ten years, and probably beyond.

The accelerating pace of grid-scale deployments has been enabled by the dramatic decrease in the cost of lithium ion battery storage systems since 2010 (Figure 6-23) addressing a range of needs, including resource adequacy (capacity), frequency regulation, and others. A lithium ion battery is a type of electrochemical storage device that stores energy during charge transfer reactions in the electrode structure. In a lithium ion battery cell, the cathode (negative electrode) and anode (positive electrode) are separated by a polymer separator and liquid organic electrolyte (Figure 6-24). There is also a, copper and aluminum current collectors, and packaging materials to enclose the material. The anode is typically a graphitic carbon electrode that holds lithium in its layers; the cathode is a lithium-intercalation compound, such as an oxide, that forms a layered structured with lithium ions. During the charging process, lithium ions are driven through the electrolyte, across the separator membrane, from layered oxide anode to intercalate into the graphite layers of the cathode, creating a voltage potential across the two electrodes. The process is allowed to reverse during the discharge process, releasing storage energy.

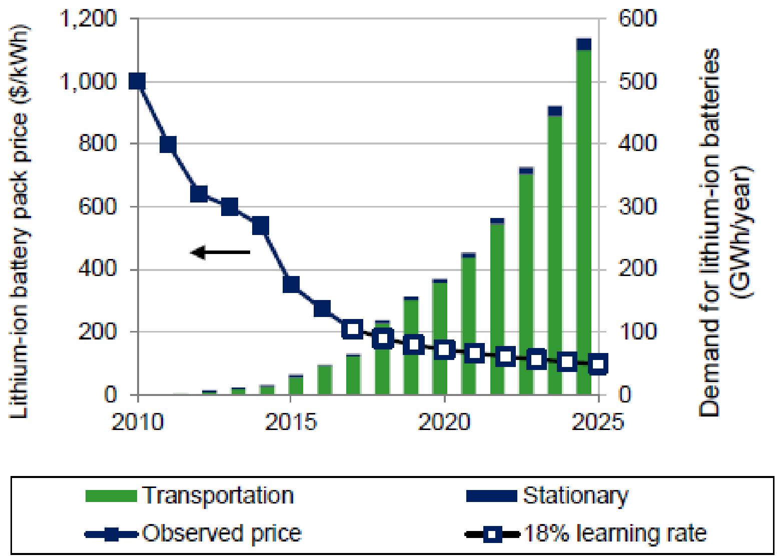


Figure 6-23
Lithium ion battery costs (pack-level), observed and projected (based on 18% learning rate); and forecast Li ion battery demand. (Source: EPRI, based on data from BNEF [11] Originally published in [12].)

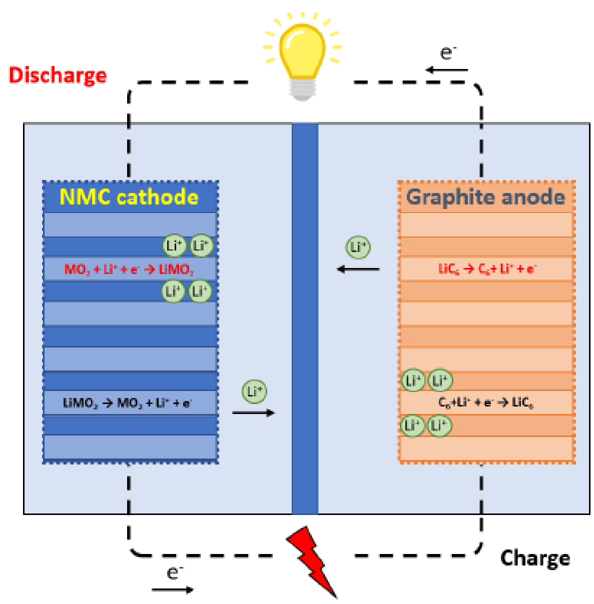


Figure 6-24
Diagram of a lithium ion battery with NMC cathode.

There are several well-defined chemistries for lithium ion batteries that have been developed over the last several decades. Thus, the term “lithium ion battery” describes a general type of device, rather than a single device with a well-defined composition of materials.

Table 6-5 surveys the different lithium ion battery chemistries that have been successfully developed for commercial use. Further detail about different Lithium ion batteries chemistries, and detailed cost considerations, is provided in EPRI’s 2018 Energy Storage Technology and Cost Assessment [13].

Table 6-5
Technology overview for commercially available lithium ion battery chemistries

Lithium Ion Chemistry	Cathode / Anode Material	Comments
NMC	$LiNi_xMn_yCo_{1-x-y}O_2$ / graphite	High energy density Can be tailored to serve energy or power purposes Good combination of energy, power and cycle life Evolving towards NMC combinations that are leaner in cobalt content due to expensive raw material cost of cobalt
NCA	$LiNiCoAlO_2$ / graphite	High energy density Good power density Moderate thermal stability Good lifespan
LMO	$LiMn_2O_4$ (spinel) / graphite	High power and high current discharge capabilities Less expensive raw material cost Lower energy density Moderate cycle life
LFP	$LiFePO_4$ / graphite	Lower-rated cell voltage Lower energy density Lower temperature to thermal runaway due to olivine crystalline structure High power capability Non-toxic cathode Lower cost of raw material
LTO	Various / $Li_4Ti_5O_{12}$	Utilizes titanate as anode Good power and chemical stability Very expensive due to cost of titanium Enables fast charging Lower cell voltage and lower energy density
LCO	$LiCoO_2$ / graphite	High power capacity Short calendar life High material cost due to high cobalt content Lower thermal stability

Sodium-Sulfur Batteries (NaS)

Several bulk and transmission connected energy storage projects have been installed using sodium-sulfur batteries [14] [15]. However, this technology has faced some uncertainty due to safety issues, and there have been no deployments in the U.S. since 2013. Two sodium-sulfur systems (Figure 6-25) were recently commissioned in Japan (the home country of major sodium-sulfur battery developer NGK Insulators), including a 50 MW, 300 MWh system in Buzen [16].

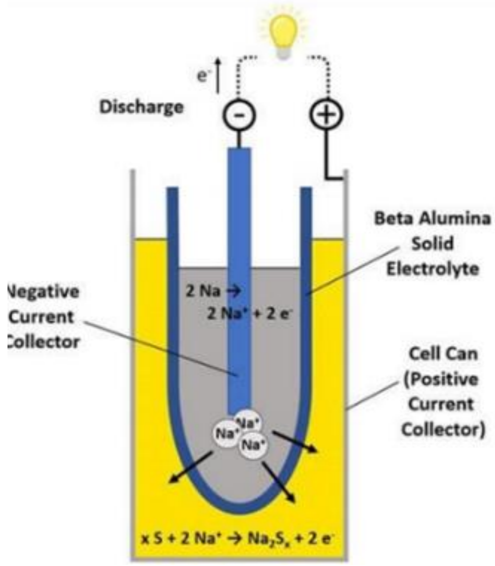


Figure 6-25
Sodium sulfur technology

Flow Batteries

Flow batteries are a type of rechargeable energy storage device in which the electroactive species are pumped from external storage tanks through an electrochemical cell, where the electrochemical reaction takes place to store or discharge energy (Figure 6-26, Figure 6-27).

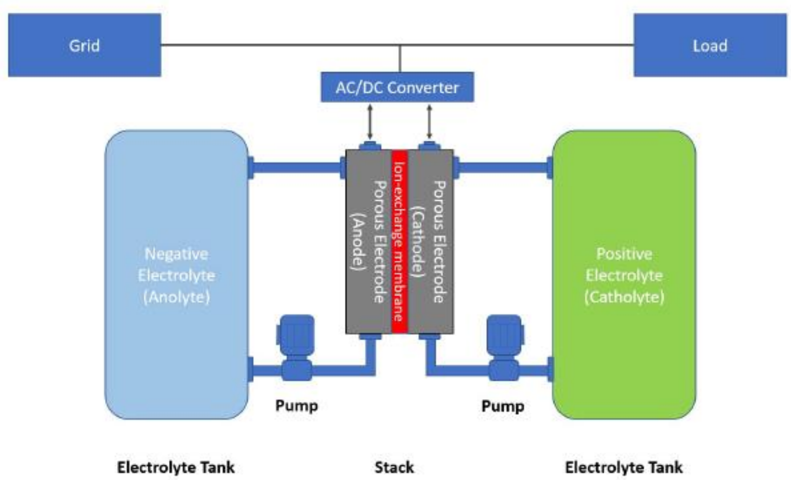


Figure 6-26
Schematic of a single-cell flow battery

A flow battery system comprises electrolytes stored in external tanks, and pumps that circulate the electrolytes through the battery stack, which contains an ion exchange membrane (Figure 6-26, Figure 6-27). When the system is charging or discharging, the active species in the two electrolytes are changing their oxidation state by transferring electrons to or from the electrode surfaces inside each cell. Simultaneously, ions flow through the ion exchange membrane, maintaining charge balance on both sides of the cell. During the charging process, electrons are harvested at the negative electrode (oxidation) and transferred to the positive electrode, where they convert the cationic species to a lower oxidation state (reduction). During discharge, the flow direction of the electrons is reversed, and the active species return to their initial oxidation states.

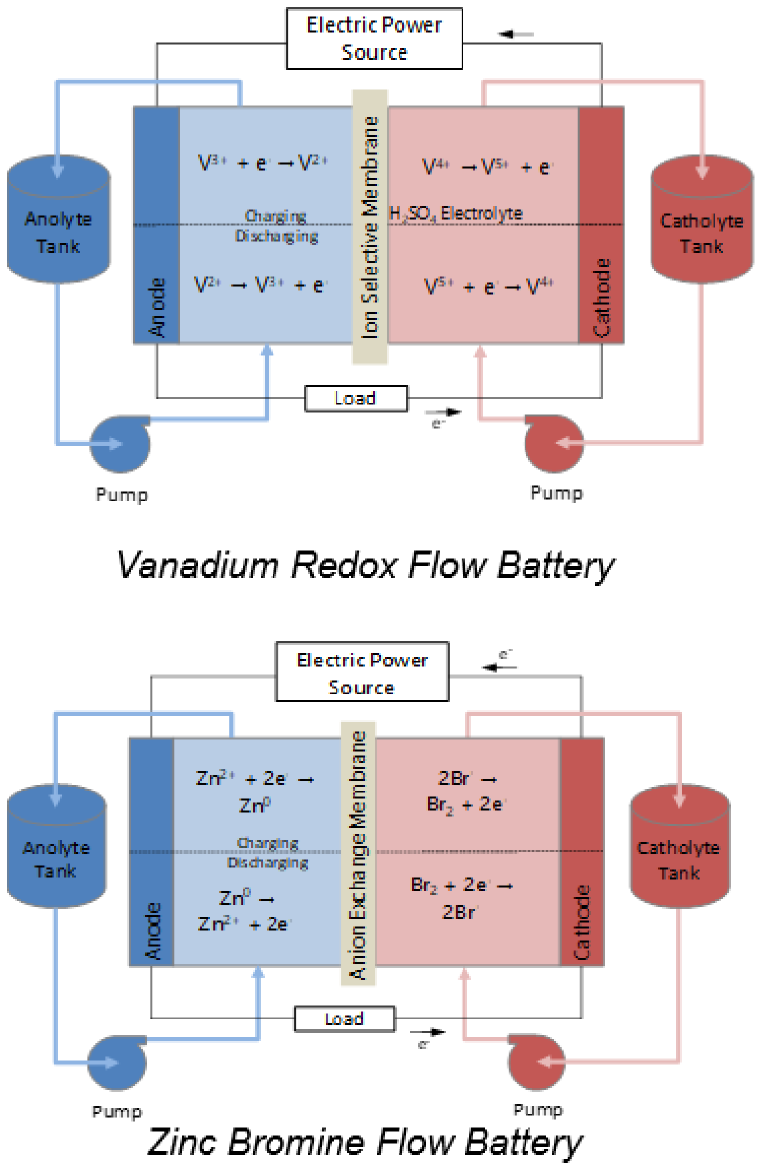


Figure 6-27
Flow battery schematic for Vanadium Redox & Zinc Bromide Flow Battery

The modular nature of the internal cells of a flow battery are connected in series and parallel, thus providing flexibility in meeting distinct voltage and current requirements for a specific application. Adding more stacks to a flow battery increases the power capacity of a flow battery installation. In contrast, adding more electrolyte volume to a system design (by increasing the size of the electrolyte tanks) provides additional energy capacity, enabling longer duration of the discharge at the same power rating for longer-duration applications. Flow batteries typically have discharge durations of four hours or longer.

Several different chemistries are being developed for commercial flow battery systems [17]. The four primary flow battery technologies starting to enter market applications are described in Table 6-6, with relative advantages and disadvantages. Included are hybrid flow batteries (or "semi-flow" systems), which describe flow battery systems where one of the active components undergoes a phase change during operation the battery; as an example, the zinc plating/deplating in a zinc-bromine hybrid flow battery. The most economical use of a flow battery is for long-duration applications with regular (daily) deep cycling. So far, most flow battery deployments are systems with less than one megawatt of capacity – far smaller than typical bulk energy storage facilities. However, recent deployments have been growing in size: Two 2 MW, 8 MWh flow battery systems were commissioned in the U.S. during 2017, and two more projects have been announced for future construction. If manufacturers achieve further cost declines, and deployed systems demonstrate reliability, flow batteries may continue to mature as a bulk energy storage option.

Table 6-6
Flow battery technology overview

Flow Battery Chemistry	Comments
All–Vanadium	Limited solubility of Vanadium in electrolyte. Expensive raw material. Low cell voltage limits power output. No cross contamination
Zinc-Bromine	Hybrid flow battery. During charge, elemental zinc is plated on the cathode. Requires full discharge every few days Higher energy density
Zinc-Iron	Hybrid flow battery Elaborate coating process for electrodes, and extensive separator technology required (salt bridge). Low-cost electroactive components. Non-toxic materials. Low energy density
All--Iron	Hybrid flow battery. Low cell voltage, Fe^{2+} is susceptible to oxidation in solution Low-cost electroactive components. Non-toxic materials, No cross contamination

Flywheel Energy Storage

Flywheels (Figure 6-28) store energy in the angular momentum of a spinning mass. During charge, the flywheel is spun up by a motor with the input of electrical energy; during discharge, the same motor acts as a generator, producing electricity from the rotational energy of the flywheel.

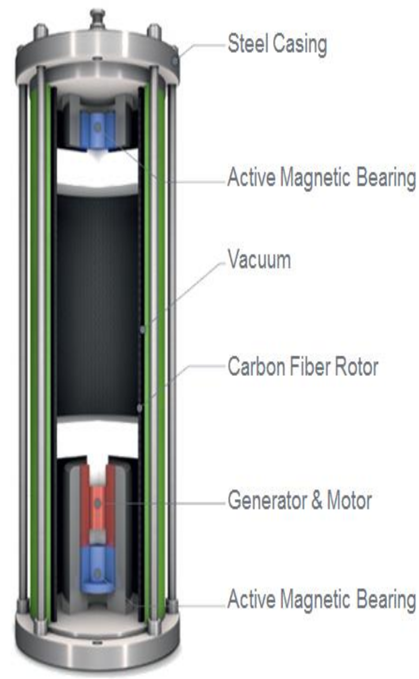


Figure 6-28
Integrated flywheel system package cutaway diagram (Courtesy of Stornetic)

Flywheels have several advantages over electrochemical batteries. Most products are capable of several hundred thousand full charge-discharge cycles and so enjoy much better cycle life than batteries. They are capable of very high cycle efficiencies of over 90% and can be recharged as quickly as they are discharged. Since the energy sizing of a flywheel system is dependent on the size and speed of the rotor, and the power rating is dependent on the motor-generator, power and energy can be sized independently. The downside to flywheels comes from their relatively poor energy density and large standby losses.

Flywheels have predominantly been used in power quality applications, in which flywheels provide ride-through capability for momentary voltage sags and interruptions. Many systems incorporate both flywheels and generators. The flywheel allows ride-through of interruptions up to about 15 seconds duration. This time also allows enough time for a generator to come on-line for longer interruptions [18-19]

Short-duration flywheels have also been used to serve fluctuating loads at the distribution level, particularly loads related to mass transit. Electric service to mass transit often experiences load fluctuations related to electric trains leaving and stopping at stations. There is also an opportunity for demand reduction and energy recovery via regenerative braking. Flywheels can be set up on the electric bus serving a mass transit station, so as to accept energy released by the train during a stop, and then release it to accelerate the train as it leaves. This reduces the electric demand on the local distribution system, allowing reduction in substation capacity, better utilization of existing T&D assets, and deferral of construction of new capacity. A prototype system of this design was installed by the New York Power Authority (NYPA) and New York City Transit (NYCT) in 2001. The flywheel system, produced by Urenco Power Technologies, consisted of ten 100-kW flywheels, together storing 5 kWh of electrical energy. The system operated successfully for three years and was removed only when the vendor exited the flywheel market and withdrew their flywheel products from the market.

More recently, flywheels have been proposed for longer duration applications. Beacon Power Corporation, a manufacturer of high energy-density flywheels, is proposing flywheels for frequency regulation applications at the transmission level. This application is being tested in upcoming demonstrations in New York, funded by the New York State Energy Research and Development Authority (NYSERDA), and in California, funded by the California Energy Commission (CEC) [20]. There are no plans at present to use long-duration flywheels in distribution-level applications.

Ultracapacitors

Ultracapacitors, also known as supercapacitors, electrochemical capacitors, and electric double layer capacitors (EDLC), are devices that resemble very large capacitors in the way they perform electrically. This technology allows capacitors with very high capacitance, measured in farads or even thousands of farads, but at relatively low voltages, between 1 and 3 V. High voltage ultracapacitor systems must be built by placing individual cells in series to produce the desired voltage.

Ultracapacitors are generally characterized by longer cycle life and higher power density than electrochemical batteries, but much lower energy density. At present, they are also quite expensive, and require control and power electronics for proper operation.

Present ultracapacitor products are appropriate for short-duration applications, such as ride-through for power quality. Investigators have also researched their use for voltage stability in conjunction with Flexible AC Transmission System (FACTS) controllers. This application, similar to the D-SMES technology described earlier, uses real power injection to aid in maintaining voltage stability during a disturbance.

Ultracapacitors have also been used to stabilize voltage in the presence of high-power loads, such as the power draw from trains at mass transit stations. This is similar to the mass transit application of flywheels described earlier. The ultracapacitor system captures energy from the breaking of a light rail vehicle and stores it until it is necessary for accelerating a vehicle. This reduces the effect of acceleration and braking on the local electrical distribution system, allowing reduced distribution capacity and better utilization of existing assets.

Superconducting Magnetic Energy Storage

Superconducting magnetic energy storage (SMES) store energy in magnetic fields produced by continuously circulating current in a superconducting coil. Although it is theoretically possible to use SMES systems for large-scale load shifting applications, such an application would require very large systems, and would not be viable unless the price of the technology were substantially reduced. For this reason, SMES technology has mostly been implemented for very short-duration discharges on the order of seconds.

At present, the only commercially available product using SMES is the D-SMES system produced by American Superconductor. This product is designed to provide reactive power for voltage support at the distribution level, with real power injection available to support the line during disturbances. When needed, the D-SMES can deliver 3 MW for 1 second. SMES units have also been used for power quality applications, to allow ride-through of voltage sags for individual customers.

Technology Maturity

Figure 6-29 summarizes the technology maturity of different energy storage technologies.

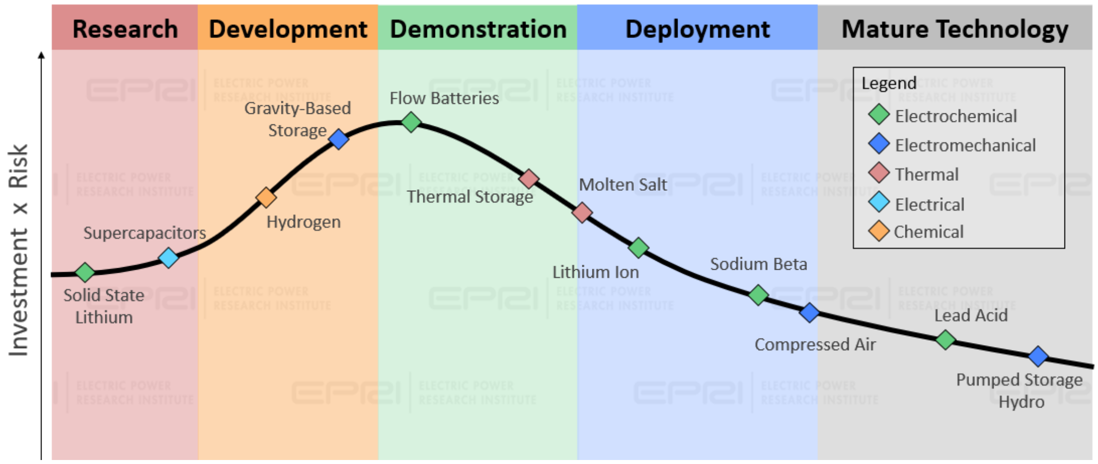


Figure 6-29
Maturity levels of different energy storage technologies

Overview of Applications

Energy storage systems (ESS) can provide a variety of grid and market services, largely due to ESS technologies' flexibility and modularity. Following are the key drivers for ESS deployment

- Lithium-ion battery costs are continuously decreasing and may be near a tipping price point
- Retirement of fossil and nuclear facilities coupled with renewable penetration creates new flexibility needs which storage can help satisfy
- Utilities are deploying storage as an alternative to generation peaking capacity and to defer infrastructure upgrades
- Federal and state policies are driving action towards the deployment of storage

Energy storage Provides Services (Figure 6-30) with a Range of Energy and Locational Requirements. Following is a list of services grouped by non-wires alternative (NWA), reliability services, and market services.

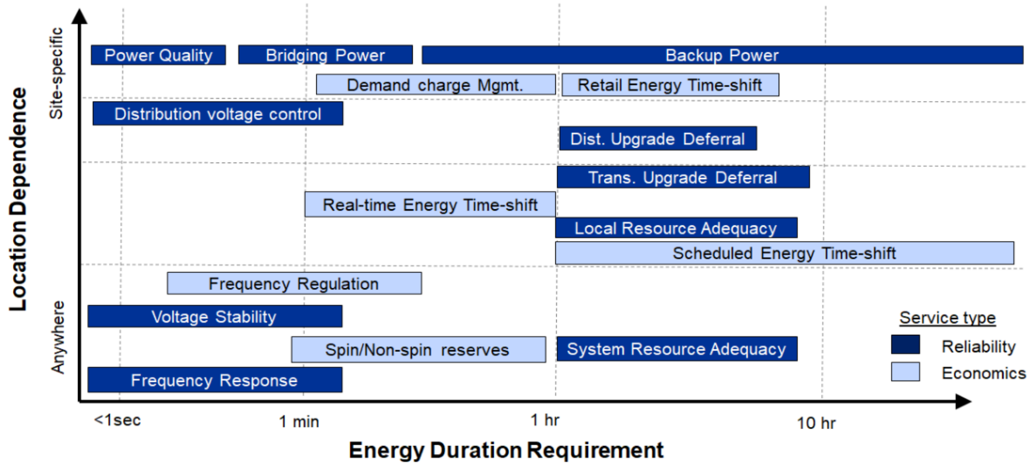


Figure 6-30
Energy storage grid services

T&D Non-Wires Services

1. Off-Shore-Wind Integration
2. Upgrade Deferrals
   - Peak Shaving
   - Load pocket relief
   - Transmission Congestion relief
3. Voltage/Reactive Power Support
4. System reliability improvements

Reliability Services

1. Grid Stabilization/Balancing
2. Transmission Voltage/Reactive Power Support
3. System Restoration
   - Energy storage for existing black start units
   - Energy storage considered as a new black start unit for system restoration support

Market Services

1. Capacity Firming
2. Spinning Regulation
3. Energy Arbitrage
4. Renewable Energy Time Shifts
5. Peaking Capacity
6. Reserves/Capacity
7. Production Cost Savings
8. Reduced fossil-fueled power plant operation flexibility/cycling

Table 6-7 summarizes the range of applications (by grid domain) where energy storage can provide these services. The table also includes a planning horizon for the timing of the dispatch decision, as well as the duration for the service's energy requirement. These criteria are important when analyzing the relative competitiveness of an ESS compared to incumbent technologies, particularly when the ESS project is being considered for supplying multiple services.

Table 6-7
Applications for advanced energy storage systems

Service	Grid Domain	Market Domain	Timing of Decision	Energy Duration Requirement
Resource Adequacy	Generation	Wholesale/ Resource Adequacy (RA)	3 years to 9 months ahead	Hours
Day-Ahead Energy Time Shift			Daily	Hours
Real-Time Energy Time Shift			System Operations	Minutes to Hours
Frequency Regulation				Minutes to Hour
Frequency Response				Minutes
Spinning Reserve				Minutes to Hour
Non-Spinning Reserve				Minutes to Hour
Flexible Ramping				Minutes
Black Start/System Restoration				Minutes
Transmission Capacity Investment Deferral	Transmission	Utility T&D	5–15 years ahead	Hours
Transmission Congestion Relief			Months ahead to real-time	Minutes to Hours
Transmission Voltage/Reactive Power Support			Real-time	Seconds to Minutes
Distribution Capacity Investment Deferral	Distribution		3–10 years ahead	Hours
Distribution Equipment Life Extension			3–10 years ahead	Hours
Distribution Losses Reduction			Day-ahead to real-time	Minutes to Hours
Distribution Voltage Control			Real-time	Seconds to Minutes

Subsequent section provides details on some of the more common use cases for transmission connected ESS.

Generation Services

Energy storage contributes to the generation segment primarily through providing resource adequacy capacity, shifting energy in time between low and high energy prices, and ancillary services. Energy storage can provide energy time shifting services in the day-ahead market and the real-time market. Energy shifting involves procuring energy at an inexpensive price and then discharging it at times when it is more valuable. This occurs typically on a diurnal basis in most U.S. power markets. Real-time load shifting involves dispatching the ESS to supply energy at peak demand times in order to meet short-term demand.

Energy storage may also participate in wholesale markets to provide the ancillary services, including frequency regulation, frequency response, spinning and non-spinning reserve, flexible ramping, and black start. The eligibility and requirements for energy storage to participate in these markets is based on the ISO market participation rules, some of which have not yet been explicitly defined for storage. FERC Order 841, "Electric Storage Participation in Regional Markets" issued in February 2018, will catalyze rules for energy storage participation. [21] ISO/RTO compliance filings are due in December 2018 and implementation by December 2019. (Separately, the ISO/RTO Energy Storage Market Modeling Working Group recently surveyed ISOs and RTOS on how they are incorporating electricity storage resources in electricity market clearing software, future plans, and key related research questions [22].

An ESS is not limited to providing just one generation service — it has the potential to stack multiple services.[23] For example, an ESS can provide resource adequacy capacity instead of the incumbent natural gas-fired turbine, an application that typically results in low capacity utilization. The same ESS potentially can also provide ancillary services or other grid support when not being used for capacity. However, since storage is an energy-limited resource, the contribution to a system's capacity may be dependent on energy duration and regional load characteristics [24].

T&D Services

Transmission Line and Load Capacity Deferrals: The most prominent application for energy storage at T&D level is load shifting. The two most common are *peak shaving* and *load leveling*. In this application, the transmission planner is seeking to avoid a conventional system upgrade by using the energy storage as a load or active power injection to defer the power flow across a specific section of the transmission system through the use of an energy storage device. By controlling the charging and discharging profile of the energy storage device, the transmission planner may be able to defer the construction of a new transmission path; the reconductoring of an existing transmission line; or upgrade of a transformer or other substation components. The deferral will not be indefinite and must be targeted for a specific year or length of time in order to provide a time horizon to complete the planning study. This approach is sometimes referred to as non-wires alternative (NWA).

- <u>Transmission Line Deferrals</u>: In this application, the energy storage is being added to the system at either the transmission or distribution level to defer or avoid the need for a transmission system upgrade, i.e. the construction of a new transmission line or transformer, or the upgrade of an existing line or transformer. For the purpose of illustration, a transmission line or transformer deferral scenario could occur on the transmission system as follows. An outage of any of the parallel transmission paths results in an overload of the online element. An outage of the line from Bus 2 to Bus 1 results in the overload of the transformer from Bus 3 to Bus 4 and vice versa (Figure 6-31). The traditional solution to mitigate the overload during the contingency condition is to construct a parallel path from Bus 2 to Bus 1, so that the outage of either one of the lines or the transformer does not result in an overload condition. An alternative approach, using energy storage as the NWA, will be to install the device at either Bus 1 or Bus 5 (both load centers) and defer the load locally to prevent the overload condition

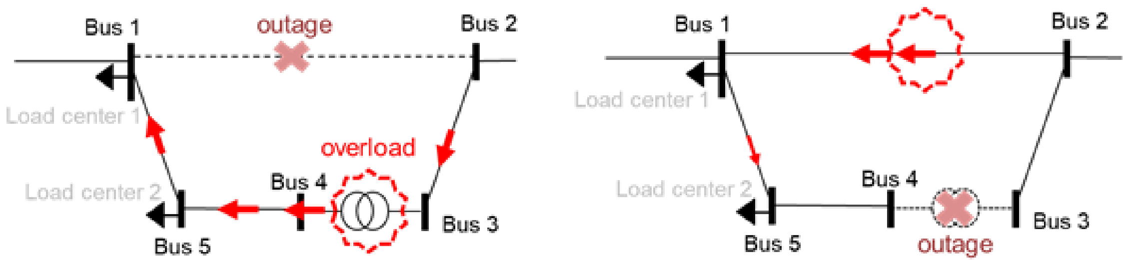


Figure 6-31
Example transmission line deferral under N-1 contingency

- Load Capacity Deferral: The other deferral application for transmission-connected energy storage is to shift or defer load over certain periods of time at a specific node in the system. The aim of peak-shifting or load deferral using energy storage would be to increase the utilization of cheaper generation resources such as wind or PV while decreasing the burden on the remaining synchronous generation in the system. The analysis process would follow a similar set of steps set out for the transmission line deferral project. However instead of trying to defer the construction of a new transmission element, a capacity deferral would simply look to site energy storage at a location such that load could be served during peak conditions on the transmission system, reducing the flow of active power across the transmission system elements.

Active and Reactive Power Support Using Energy Storage: The primary capability of energy storage systems is to deliver controlled active power to the system. Energy storage systems can also provide fast-frequency response as a primary or secondary service for power systems where primary frequency response support is needed. Once an energy storage system has been sited, further analysis is required to configure the active power controls in order to ensure a response characteristic that satisfies the frequency response requirements of the operating region. The controller settings of the energy storage system are a key consideration to ensure that it provides adequate frequency response. Energy storage systems are flexible active power devices and can be configured to provide the system with regulation services and/or fast-frequency response[11] in line with the regional grid code requirement. In an energy storage system where the primary service is fast-frequency response, if properly tuned, the entire rated output of the energy storage device may be directed toward active power injections in response to a change in system frequency. Depending on the inverter system, the controllers must be properly tuned to ensure that the rated power output can be delivered to the system at the point of interconnection. For example, if a 100 MW energy storage device utilizes droop control with a generic controller, a

[11] Fast frequency response, or FFR, is a term often used to define a power response proportional to frequency deviation that occurs without thermal or hydraulic delays.

5% droop setting with an observed network frequency deviation of 59.85 Hz, would only inject 5 MW of the rated power output of the ESS to the system. To ensure 100% of the rated power for the same frequency deviation is delivered by the ESS, a droop setting of 0.25% would be required by the controller. An energy storage device can also dynamically inject reactive power to support local voltage at the transmission network. To accurately assess the dynamic voltage impacts and adequately size the MVAr capability, both steady-state and dynamic analysis of the storage interconnection are required.

Voltage Support: ESSs can also reinforce the grid by providing voltage support and system stability. Voltage regulation requires that the utility maintains the voltages at the generation and load ends of transmission lines within 5% of each other. Voltage support involves the injection or absorption or reactive power (VARs) into the grid to maintain system voltage within the optimal range. This is usually done with static capacitor banks, although the use of other solutions, such as FACTS devices, has expanded in recent years. Energy storage systems use power conditioning electronics to convert the power output of the storage technology to the appropriate voltage and frequency for the grid. If the power conditioning electronics are designed for four-quadrant operation, they can also be used to absorb or inject reactive power, effectively acting as a FACTS device. While this isn't a benefit of energy storage per se, it is an additional benefit that can be gained when an energy storage system is present.

Hybrid Renewable Generation and Energy Storage Sites: Storage may also be co-located with other generation or renewable resources to improve their combined value proposition. Co-locating energy storage with inverter-based renewable generation is mainly focused on renewable curtailment during light load condition as well as providing a less variable, smoother active power output from the generating facility. Co-locating an ESS with natural gas generators can leverage existing interconnection infrastructure and avoid potentially contentious siting issues. The co-located storage can reduce thermal derating of the generator, reduce generator cycling for life extension, and reduce the amount of time the generator operates at partial load, which reduces fuel use and greenhouse gas emissions. The storage can potentially provide ancillary services with the generator. An ESS paired with a variable renewable resource, such as solar or wind, can take advantage of design efficiencies and tax incentives available to qualifying renewable technologies to lower its costs. A co-located ESS enables the renewable energy resource to be dispatchable, though the net effect of this approach may be the same as standalone storage, depending on the system configuration.

Blackstart Generation and Restoration Support Using Energy Storage: Another potential application of battery energy storage device at the transmission level is to provide recovery support to a system in a partial or a complete blackout condition. An energy storage system can assist in the blackstart capability of a synchronous generator. It may also help in the energization of transmission lines or critical elements along the restoration paths to critical infrastructure. For a battery energy storage device that is interconnected to the transmission system, this definition requires that the inverter is capable of injecting and controlling current to support the in-rush requirements of certain types of load.

- Energy storage supporting the start-up of an existing blackstart: Blackstart units rely on local diesel generators to start the plant auxiliary equipment (motors, pumps, drive, etc.) that is critical to the functioning of a thermal generating station. An energy storage device can support start-up of the plant auxiliaries. The auxiliary loads required for plant startup draw high current, and the inverter of the energy storage device must be able to provide sufficient voltage and frequency control to ensure stable operation.

- Energy storage acting as an new blackstart unit: Energy storage could be re-classified as a blackstart unit, provided that the energy storage system can adequately supply power (both active and reactive) to all of the plant auxiliaries required for start-up of a generating station. Along with the supply of power to the start-up loads, the energy storage device can also operate in charging mode and act as a variable load, to help maintain load/generation balance or for voltage control during early restoration.

Energy Storage as Restoration Resource: Restoration of power system from a blackout condition is typically performed by sequentially re-energizing network components such as transmission lines, transformers, etc. through a series of switching actions to provide electrical pathways to critical loads or non-blackstart units. The technical capabilities of battery energy storage systems are well suited to support this re-energization process. For example, as a line switches into service, the capacitive line charging of the high-voltage transmission line can result in significant over-voltages along the restoration path. An energy storage device, if located along restoration path, can potentially be used to control this over-voltage using the dynamic reactive power control capability of the device. In addition to providing voltage or reactive power control, an energy storage device can discharge to provide back-up power to critical substation equipment – i.e. the breakers, switches, and protection equipment that will be required to securely maintain the restoration path.

Energy Storage Technology Technical Characteristics & Performance Overview

To assist resource planners and others evaluating storage as an alternative, it is important to understand the underlying technology and performance parameters as well as expectations for future trajectories. Key parameters (Table 6-8) are those that impact the overall lifecycle cost of the system, as well as those that impact the ability of ESS to perform grid services and capture benefits.

Table 6-8
Technical characteristics & attributes of merit

Attribute	Economic Implication
Energy or Power Density	Material cost, Land use, and Balance of System
Cost Structure	Cost versus benefits
Charge/Discharge Efficiencies	Cost of charging, thermal management
Toxicity, Flammability, or Corrosiveness	Safety infrastructure, PPE, and disposal costs
Degradation, Cycle Life, and Reliability	O&M and replacement costs
Technology Maturity	Risk and uncertainty, “soft” costs of new practices
Geographic Requirements	Scalability and replicable solutions

Technology developers and application specialists use several different metrics to describe technologies, depending on the application:

- **Life:** Calendar life and cycle life degradation are separate vectors
  - *Cycle life*: Describes the number of times an energy storage device can be charged and discharged
    - For lithium ion, cycle life is governed by corrosion and fatigue, primarily on the lithium metal oxide electrode
    - Frequent or deep cycling will degrade some storage faster (e.g. Li ion, lead acid)
    - Understanding the duty cycle is important to estimate asset life
  - *Calendar life*: Years until the storage system operates before degradation beyond application requirement
    - For lithium ion, calendar life is governed by growth of the SEI layer on the surface of the graphite electrode, which is dependent on temperature and state of charge. SEI later grows faster at high temperature and high state of charge.
    - Higher temperature and higher average state-of-charge will degrade system faster, particularly if concurrently high SOC and temperature
    - Battery degradation may occur at an accelerated rate later in the life
      - Increased corrosion = decreased capacity = higher DOD in a fixed application = accelerated corrosion
      - Increased impedance = increased internal heating = increased SEI formation = accelerating impedance increase
      - May have significant implications on prospects for second life system
- **Footprint** impacted by Power Density, Energy Density, Packaging Choice, Spacing
- **Cost** per energy stored ($/kWh) and cost per capacity stored ($/kW) including Operations & Maintenance cost (O&M) and End of Life (EOL)
- **Efficiency:** Ratio of the delivered discharge energy to the delivered charge energy, including facility parasitic loads. Several factors will impact the measured efficiency including ESS losses, conversion, auxiliary loads, duty cycle
- **Response Time and Ramp Rate** Fast acting energy storage systems may perform dynamic grid services (like frequency regulation) better than conventional alternatives
- **Safety**: system integration is a key of safety. Types of hazards include fire, chemical, stranded energy, electrical, physical.

Metrics such as these are often used in side-by-side comparisons of very disparate technologies. Such comparisons can be misleading, since performance of these technologies can vary widely depending on the conditions under which they are assessed. In fact, making “apples-to-apples” comparisons of energy storage technologies is quite difficult, for a number of reasons:

- Performance depends on the design of specific products. For example, flywheels can be designed to deliver a great deal of power for a short period of time or a small amount of power over a long period of time. For this reason, most metrics must be provided as ranges rather than as single numbers.

- Performance depends on the conditions of use, including the application profile and environmental conditions. For example, a lead-acid battery may deliver 2000 cycles at 50% depth-of-discharge and 25º C, but is unlikely to achieve the same performance at 100% depth-of-discharge and 40º C.
- Products based on different energy storage technologies are rarely direct replacements for each other. Switching from one to another can require significant changes in other parts of the system. For example, ultracapacitors may require additional power electronics in deep-cycle applications, while batteries may not. The cost of the additional power electronics should be included in the $/kWh figures used in the comparison.
- In some cases, products are not mature or have not been built at the scale required for use at the utility level, so the true capabilities of a technology are unknown. In general, the earlier stage the technology, the more aggressive the claims made for it.
- Any cost comparison must include costs over the full lifecycle of the system, including initial capital cost, operations and maintenance (O&M) costs, and replacement costs. Comparisons describing only initial costs are misleading.

Storage Technology Parameters

Energy storage technologies have unique attributes compared to other generation resources. Understanding these parameters can assist in making comparisons among different options, particularly in determining which storage technology best meets a particular grid service. Table 6-9 provides definitions for key performance characteristics and their potential impact on lifecycle project costs. [25] For example, cycle life and calendar life for lithium ion, and time between overhauls for flow battery, potentially have the greatest impact on maintenance costs among the parameters in Table 6-9.

It is important to clearly define these parameters, especially what triggers end-of-life (EOL), as such definitions can vary between battery chemistries and among manufacturers. For example, lithium ion technologies typically define EOL as the point where the stored energy reaches a certain percentage of the initial capacity rating (e.g. 70%, 60%). After the defined EOL, the system may experience accelerated degradation even though it can continue to operate. A universally accepted definition for EOL of a flow battery does not exist yet. Flow battery manufacturers may provide cycle life and calendar life metrics as a means to compare to lithium ion; however, the questions to ask are: what is the life of the major components or time between overhauls, and what is the impact of cycling and time? Additionally, all these metrics can be difficult to estimate as they may change given environmental conditions, balance of system design, battery management system (BMS) design, or other factors external to the underlying storage medium.

Roundtrip efficiency (RTE) directly impacts operating costs, as systems with lower RTE will incur higher charging costs during operation. Additionally, some incentive programs require participating systems to maintain a minimum RTE in order to quality for their incentive. For instance, California's Self-Generation Incentive Program (SGIP) requires the ESS to maintain a RTE greater than 69.6% in the first year of operation, and a minimum ten-year average of 66.5%.

Table 6-9
Energy storage definitions of performance characteristics and impacts on their use source: EPRI

Performance Characteristics	Definition	Potential Impact
Auxiliary power	Also known as "housekeeping power", the load that is required to maintain the system during normal operations; can include thermal management, communications, and monitoring system.	Auxiliary power requirements result in energy losses and decreased system efficiency.
Calendar life (for lithium ion)	The number of years until the energy storage system reaches its end-of-life (EOL), independent of cycling degradation.	Storage systems with longer calendar life can serve long-term needs. Similar to cycle life (below), systems requiring more frequent replacement increases maintenance costs.
Charge power	The maximum steady state active power at which the ESS can continuously absorb at the AC terminals of the PCS.	Limitations in charge power or rate may impact the storage systems ability to perform dynamic responses such as frequency regulation, and its ability to perform multiple cycles per day.
Cycle life (for lithium ion)	The number of cycles (typically given at specified depths of discharge) that the energy storage system can perform until EO and is independent of calendar life degradation.	Storage systems with longer cycle life can undergo more charge/discharge cycles and be more suitable for use cases with daily cycling such as energy time shift. Systems with shorter cycle life may require more frequent augmentation or component replacement, increasing maintenance expenses. Depending on duty cycle, cycle life may not be a concern as the system may reach the end of its calendar life ahead of end of cycle life.
Energy density	The amount of energy stored per unit mass occupied by the system, (kWh/kg); can be expressed for per volume basis for other energy sources, (kWh/L).	If space is a concern, such as in urban areas, substation fences, or commercial facilities, systems that have higher energy density may be more desirable because they could have a reduced footprint. However, based on the packaging, two systems of the same technology may have different system footprints (e.g., ISO containers vs. dedicated building).
Power density	The amount of power delivered on demand per unit mass (kW/kg).	High power density chemistries are lighter for high power usage; can be important for transportation, less for stationary applications.
Roundtrip efficiency (RTE)	Total AC roundtrip efficiency of the facility is defined as the ratio of the delivered discharge energy to the delivered charge energy, including facility parasitic loads. Note: RTE varies at different charge/discharge rates.	More energy can be extracted per charge/discharge cycle for systems with higher RTE. RTE has a larger impact on applications that are more frequently cycled and have higher energy throughput as RTE will impact cost of charging. RTE assumptions are also important in calculating the emissions implications of energy storage.
Self-discharge rate	Rate at which the ESS will lose state of charge (SOC) while being held at a given SOC, not including auxiliary load energy (%/hour).	Systems with high self-discharge rate are less effective when idling for long duration, making it less suitable for infrequent operations and seasonal storage than systems with a lower self-discharge rate.
Time between overhaul (for flow battery)	The number of run hours or calendar time before a mechanical part or other component requires overhaul. (Time between overhaul is often used in aviation.)	Flow batteries require equipment overhauls, such as pump or stack replacement. More frequent overhauls increase operating and maintenance costs.

Lithium Ion and Flow Battery Comparison

This section provides an overview of lithium ion and flow battery technical characteristics and performance, for both current technology and that expected in 2030. A review of storage specific performance parameters for lithium ion and flow batteries, is provided. Also presented is a comparison of their fit for stationary market applications and an overview on the status of their market deployment.

Lithium ion and flow battery technologies have unique attributes that provide advantages or disadvantages for stationary storage applications. Table 6-10 list the attributes relative to the other technology. Details are discussed further below in this section.

Table 6-10
Comparative advantage and disadvantages of lithium ion and flow battery technologies

Technology	Advantage	Disadvantages
Lithium ion	• High power and energy density • Low self-discharge rate • Higher RTE	• Potential for thermal runaway • Energy capacity degradation due to cycling and time • Calendar degradation • Sensitivity to overcharging and temperature extremes (thus, requires well-designed control systems) • Some raw material costs are expensive
Flow battery	• Able to scale power and energy independently • No energy degradation • No thermal runaway	• Low power and energy density • Low roundtrip efficiency • High cost of some electrolyte material • More complex systems with pumps, plumbing, and other auxiliary components • More prone to leakage which can be potentially hazardous • May have increased maintenance costs

Table 6-11 discusses the use of lithium ion batteries and flow batteries to support grid services, given their technical parameters and status as to whether they have been demonstrated in commercial applications.

Table 6-11
Lithium ion and flow battery application potential

Service	Lithium Ion	Flow Battery
Resource Adequacy	Commercially proven for 4 hour systems, e.g., in California ISO	Well suited for long duration applications
Day-Ahead Energy Time Shift	Technically feasible, but should consider degradation impact	Technically feasible
Real-Time Energy Time Shift		
Frequency Regulation	Commercially proven, e.g., in PJM market	Technically feasible, but not likely to be used for a primary service
Frequency Response	Commercially proven, e.g., in UK and Australia	Technically feasible, but limited SOC window for high power output
Spinning Reserve	Technically feasible, but not likely to be used for a primary service; gas plus storage systems deployed	Technically feasible, but not well suited due to high self-discharge rates or auxiliary power losses
Non-Spinning Reserve		
Flexible Ramping	Technically feasible	Technically feasible, but not likely to be used for a primary service
Black Start	Commercially demonstrated	Technically feasible, but not likely to be used for a primary service
Transmission Capacity Investment Deferral	Commercially demonstrated	Technically feasible
Transmission Congestion Relief	Commercially demonstrated	Technically feasible
Transmission Voltage/Reactive Power Support	Commercially demonstrated, but not likely to be used for a primary service	Technically feasible
Distribution Capacity Investment Deferral	Commercially demonstrated	Demonstrated
Distribution Equipment Life Extension	Technically feasible, but not likely to be used for a primary service	Technically feasible
Distribution Losses Reduction	Technically feasible, but not likely to be used for a primary service	Technically feasible, but not likely to be used for a primary service
Distribution Voltage Control	Technically feasible, but not likely to be used for a primary service	Demonstrated
Demand Charge Reduction	Commercially proven	Technically feasible
Retail Energy Time Shift	Commercially proven, often a secondary service to demand charge reduction	Technically feasible
Power Quality	Technically feasible, but not likely to be used for a primary service	Technically feasible, but not likely to be used for a primary service
Backup Power	Commercially proven	Technically feasible, but not well suited due to high self-discharge rates or auxiliary power losses
Demand Response Program Participation	Commercially proven	Technically feasible
Renewable Energy Net Energy Meter Program Participation	Commercially proven	Technically feasible

Lithium Ion Battery Performance Characteristics

Table 6-12 summarizes the parameters of the lithium ion battery that may be used in a lifecycle cost-benefit analysis.

Table 6-12
Performance characteristics of lithium ion batteries

Performance Characteristic	EPRI Assumptions
Calendar Life* [%/year] and [years]	2.7%/year or 15 years
Cycle Life [# cycles at % DoD]	5,000 @ 80% DoD
Housekeeping Power [kW]	Negligible for screening analysis
Roundtrip Efficiency [%]	85%
Self-discharge rate [%/hr]	Negligible for screening analysis

*Assumes EOL is at 60% of initial energy capacity

Lithium ion systems sustain some form of erosion during every charge and discharge cycle. Different use cases have various effects on the degree of cycle life degradation. For example, performing frequency regulation may require thousands of shallow cycles per year, whereas resource adequacy capacity may require hundreds or less deep cycles. Charging and discharging at shallow depth of discharge (DoD) will have less impact on the cycle life degradation, compared to deeper DoD cycles. It can be difficult to assess cycle life as data is often provided at the cell level and extrapolated for shallow depths of discharge.

Calendar degradation occurs independent of cycling. For lithium ion systems, calendar degradation occurs more quickly with higher average state of charge (SOC) and higher operating temperature, and particularly if those occur concurrently.

Roundtrip efficiency varies based on charge and discharge power, ambient conditions, rest periods, and other factors. For lithium ion batteries, RTE is generally in the range of 80% to 90%.

Self-discharge rate and housekeeping power are often ignored for screen analyses. However, if the system is not being dispatched for extended periods of time, these factors may become more prominent and should be considered. Housekeeping power is low when ambient conditions are near 25°C, and spikes when ambient temperatures are colder or warmer than the normal operating range for the technology used, for example, near -20°C or greater than 60°C for a NMC chemistry.

Flow Battery Performance Characteristics

Flow battery systems have a wide range of performance values, partly due to the specific chemistry each technology employs. Table 6-13 summarizes the parameters of the primary flow battery chemistries that impact their lifecycle cost. These data are derived from publicly available vendor specification documents. The declaration of a specific vendor and product does not constitute an endorsement and is provided for reference only.

Table 6-13
Performance characteristics of flow batteries reported by vendors, 2018

Flow battery Chemistry	Energy Density [Wh/kg]	Roundtrip Efficiency [%]	Calendar Life [y]	Cycle Life [# of 100% DoD cycles]	Vendor, Reference Product
All-Vanadium	12.9	70	20	Unlimited over 20 years*	UET Uni.System®
Zinc-Bromine	24.5	70 (DC)	20	Not reported	Primus Power EnergyPod®
Zinc-Iron	7.1	>74	20	Not reported	ViZn Z20®
All-Iron	11.1	70 (AC) 75 (DC)	>20	>20,000	ESS Inc. 100kW/400kWh

Flow battery vendors report round-trip efficiency of 70-80%. Reporting of this key technical characteristic is not standardized among system vendors, so careful attention is warranted when reviewing vendor data, for instance to determine how auxiliary system loads are treated when determining round-trip efficiency. At this time, EPRI believes that 50-60% may be a more realistic range for overall round-trip efficiency of RFBs.

Energy Storage Deployment

Energy Storage Deployment Trends

Bulk energy storage systems are generally "front-of-meter" systems, installed in the transmission or distribution grid domains. Front-of-meter deployments in the U.S. have grown dramatically since 2013, increasing more than tenfold in both power and energy terms (Figure 6-32). (Not all front-of-meter systems are bulk energy storage; many distribution and transmission-connected ESSs have less than 10 MW capacity and/or less than four hours of duration.)

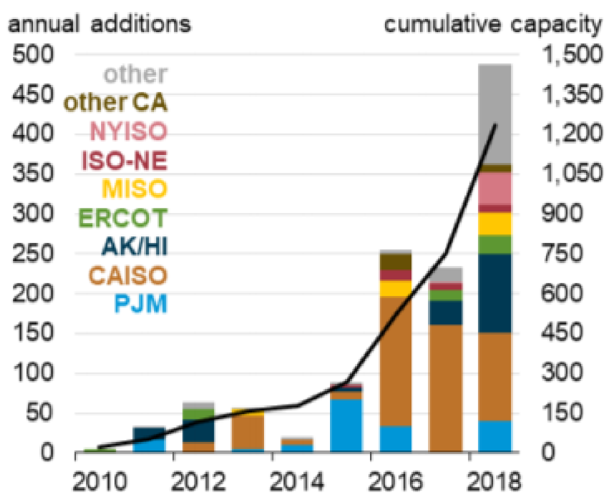


Figure 6-32
U.S. front-of-meter energy storage deployments data (Source: EIA data)

Front-of-meter systems account for about 70% of energy storage capacity installed in the U.S. through Q1 2018 by power capacity (approximately 60% by energy capacity)

Several jurisdictions have established procurement targets for energy storage. Those in North America are tabulated in Table 6-14

Table 6-14
Energy storage procurement targets in North America

Region	Year Initiated	Legislation	Implementing Agency	Procurement Target
California	2013	AB 2514 (2011)	California Public Utilities Commission	1,325 MW procured by 2020
Colorado	2019	SB 18-09 (2018)	Colorado Public Utilities Commission	Up to 15 MW per utility
Massachusetts	2018	H 4857 (2018)	Department of Energy and Resources	1,000 MWh by 2025
New Jersey	2018	A-3723 (2018)	Board of Public Utilities	600 MW by 2021; 2,000 MW by 2030
New York	2018	A 5671 (2017)	New York Public Service Commission	1,5000 GW by 2025; 3,000 GW by 2030
Virginia	2020	S.B. 851	Virginia Legislators	3.1GW by 2035
Nevada	2020		PUC Nevada	1MW by 2030
Oregon	2015	HB 2193	Oregon Public Utilities Commission	At least 5 MWh and up to 1% of 2014 peak load by 2020

The California target, AB 2514, was enacted in 2013. It has been an important stimulus for deployment of energy storage (both bulk and smaller scale). Progress towards this target is detailed in Table 6-15.

Table 6-15
Progress toward California energy storage targets: CEC inventory of Investor-Owned Utility energy storage procurement under AB 2514, August 2018 (Source: Excerpted from [27].)

Energy Storage Procurement Targets (in MW)					
Storage Grid Domain (Point of Interconnection)	**2014**	**2016**	**2018**	**2020**	**Total**
Southern California Edison					
Transmission	50	65	85	110	310
Distribution	30	40	50	65	185
Customer	10	15	25	35	85
Subtotal SCE	**90**	**120**	**160**	**210**	**580**
Pacific Gas and Electric					
Transmission	50	65	85	110	310
Distribution	30	40	50	65	185
Customer	10	15	25	35	85
Subtotal PG&E	**90**	**120**	**160**	**210**	**580**
San Diego Gas & Electric					
Transmission	10	15	22	33	80
Distribution	7	10	15	23	55
Customer	3	5	8	14	30
Subtotal SDG&E	**20**	**30**	**45**	**70**	**165**
Total – all 3 utilities	**200**	**270**	**365**	**490**	**1,325**

Lithium Ion Status of Demonstration and Commercialization

Lithium ion currently dominates battery storage deployments with more than 97% of the capacity of stationary ESS installations. Given current and projected costs, lithium ion is likely to remain in the leading position for most stationary applications for the at least the next five to ten years, and probably beyond. Examples of the range of lithium ion projects deployed or soon to be installed include:[27]

- Green Mountain Power (GMP) has a residential storage program that offers up to 2,000 customers a subsidized Tesla Powerwall (5kW, 13.5kWh) for backup power. GMP, meanwhile, is allowed to dispatch the units to reduce transmission charges during summer peak times. As of mid-2018, GMP had some 500 units installed. [28]

- The massive natural gas leak from Southern California Gas's Aliso Canyon underground storage reservoir in 2015-2016 resulted in an emergency need for regional peak power generating capacity to replace the expected loss of natural gas-fired generation. A resulting RFP process led to three major lithium ion battery ESSs being contracted and built. The projects ranged from 20-30 MW each, with four hours of duration, and they were commissioned six months following the purchase order date. [29]
- The Hornsdale Power Reserve (HPR) project in Australia is a 100MW/129MWh ESS constructed with Tesla lithium ion batteries in 2017; it is one of multiple Australian projects being deployed or planned to support grid services and variable renewable energy integration. The HPR system is being dispatched to serve South Australia's Frequency Control Ancillary Services (FCAS) market, and it has earned an estimated AU$35M in revenue during the first four months of 2018.[30]
- Florida Power and Light (FPL) has added lithium ion ESSs to two existing solar PV plants. One ESS is a DC-coupled 4MW, 16MWh system tied to FPL's Citrus Solar Energy Center in DeSoto County, Florida. This system captures solar energy that would otherwise be clipped by the PV plant's inverters, thereby increasing the solar plant production by an estimated 500+ MWh per year. [31] FPL's second lithium ion ESS is a 10MW, 40MWh battery installed at its Babcock Ranch Solar Energy Center in Charlotte and Lee Counties, Florida. The system is being used to smooth solar PV production and better match PV production with peak demand.[32]
- Pacific Gas & Electric (PG&E) received permission from the California Public Utilities Commission in November 2018 to proceed with its proposal to replace three reliability-must-run, natural-gas-fired power plants with lithium ion ESSs, including what could become the world's largest lithium ion ESS at 300MW, 1,200MWh. Combined, PG&E signed contracts for four lithium ion systems totaling 567.5MW, 2,270MWh, including 10MW that will comprise BTM storage systems. These new facilities all are contracted to be operational no later than December 2020.[33]

Flow Battery Status of Development, Demonstration and Commercialization

Flow battery projects are largely in the demonstration phase, especially within the U.S., with initial commercial deployments starting to come on-line or be announced. If flow battery technology costs decrease sufficiently, it has the potential to be competitive in longer duration applications, including resource adequacy or variable renewable energy integration (via energy time shift). However, flow battery technology has an underlying challenge compared to lithium ion batteries: unlike lithium ion batteries, which have parallel market applications in electric vehicles and portable power applications, flow battery technology does not have secondary market applications that can help reduce its costs via leveraging manufacturing scale and material inputs. Therefore, flow battery manufacturers are pursuing other avenues for cost reduction. For example, flow battery companies are taking different approaches to packaging the technology: small modular systems, which may help to achieve lower cost manufacturing if produced in scale; containerized systems (such as using ISO containers) where some are designed to be vertically stacked, relieving some of the large footprint requirements, and one-off plant designs which may be the most cost effective at scale, though create potential integration challenges. Systems are being deployed in all these configurations.

Still, several flow battery projects are beginning to be deployed, including those listed below.

- VionX, National Grid, and the U.S. Department of Energy commissioned at 3MWh vanadium redox flow battery system in Worcester, Massachusetts in October 2018. The system, which will be used to store variable wind energy and support renewable energy firming, can discharge for up to 6 hours.
- Hokkaido Electric Power Company, Inc. (HEPCO) and Sumitomo Electric Industries (SEI), Ltd. completed the installation of a 15 MW, 60 MWh demonstration project at a substation in Hokkaido, Japan. The goals of the project, which is scheduled to conclude in 2019, include evaluating the technology's performance and developing control and operational techniques for renewable integration.
- Rongke Power is manufacturing a 200 MW/800 MWh vanadium flow battery that is scheduled to be installed in Dalian, China by 2020. As of December 2017, site work on the project had commenced. The system will be able to reduce an estimated 8% of Dalian's peak load upon commissioning.

Energy Storage Deployments by Technology, System Size, and Duration

The power and energy capacities of existing ESS deployments are shown in Figure 6-33. Different regions of the plot correspond to different ESS durations (i.e. the maximum discharge duration at maximum rated discharge power). The dotted lines denote the thresholds for various system durations (one, two, four and six hours).

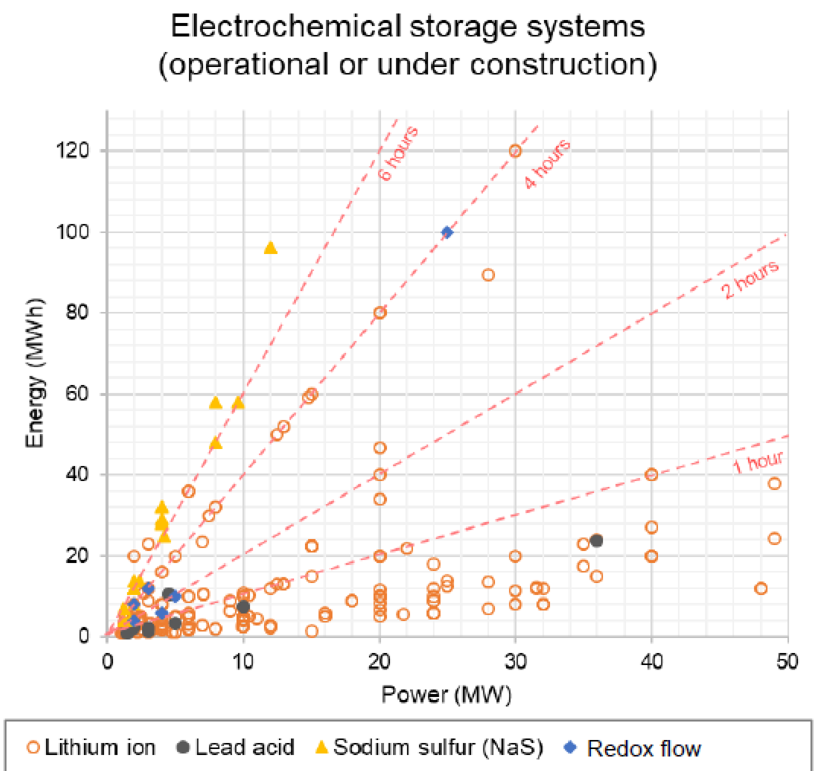


Figure 6-33
Power and energy capacities of existing energy storage system deployments using electrochemical technologies. Data source: DOE [34], GTM Research [35], EPRI research.

Several technology trends are evident. Lithium ion is the most commonly deployed technology, and most LIB systems are less than one-hour duration. This reflects the widespread deployment of Lithium ion system for short-duration frequency regulation purposes. These short-duration LIB systems range from under 5 MW to approximately 50 MW. A smaller number of longer-duration LIB systems are deployed, mostly with four-hour duration. Several MW-scale lead acid systems are also in operation. The largest is the 36 MW, 24 MWh system at Duke Energy's Notrees Wind Storage Demonstration Project [36]; most are under 5 MW, and under one-hour duration.

The set of redox flow battery (RFB) deployments shown here, while currently incomplete, accurately reflects the trend that most current RFB deployments are less than 10 MW. The 200 MW Rongke Power RFB system (planned for completion in 2020) is too large to be shown on this plot.

Sodium sulfur (NaS) batteries are generally long-duration systems (six hours or more). Relatively few NaS systems are deployed, compared to recent LIB installations. The majority of NaS installations are in Japan. Large NaS systems not shown in Figure 6-33 include the 34 MW, 238 MWh Futumata wind farm system; and a 50 MW, 300 MWh substation system in Buzen

Energy Storage Installed Cost Summary and Projections

This section provides an updated view of installed facility cost for energy storage. Figure 6-34, Figure 6-35 and Table 6-16 provide a summary overview of EPRI's projected turnkey installed EPC costs for 2019. These cost values are provided over a range that reflects how installed costs for specific projects can vary based on location, site conditions, owner or application specific requirements, supply constraints or excess manufacturing, among other factors. The main source of variation between the same technology in different applications is the capacity and energy rating. Larger, longer duration systems can take advantage of volume discounts for major components and efficiencies in design and construction. (Note that the costs presented in these two figures and following table do not include O&M or decommissioning costs.) Figure 6-34 presents costs in $/kW per the convention used for expressing generator costs. Due to energy storage being an energy limited device, costs in $/kWh are presented in Figure 6-35. The power and energy durations for the ESSs presented in these summaries represent systems that serve specific applications or use cases.

Caution should be used in evaluating installed costs simply through $/kW or $/kWh values, as scale and energy duration characteristics impact a specific project's overall economics. Installed cost can be misleading for energy storage projects given the range of power and energy capacity combinations available. Thus, installed cost should only be used to compare ESSs with the same discharge duration. For example, if installed cost is quoted in $/kW for an ESS that has little energy capacity but a large power capacity, then this value will be far lower than an ESS that has the same power capacity but more energy capacity. Additionally, when looking at cost studies, it is important to consider the scope of the installation, scale of the system, and the year the costs are estimated for, as these assumptions can vary between studies.

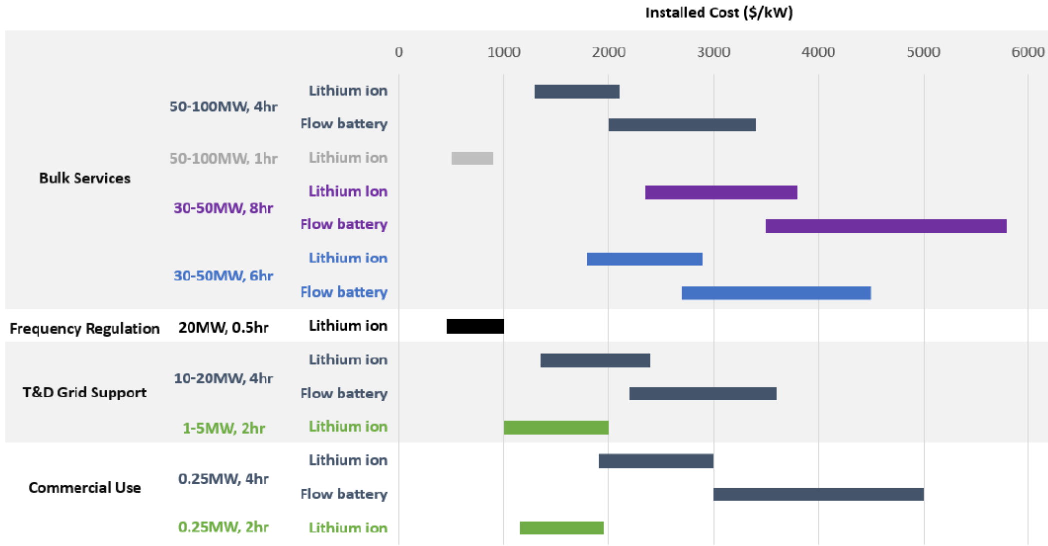


Figure 6-34
Energy storage installed cost summary per unit rated power capacity, by application, 2019 projections. *Source: EPRI*

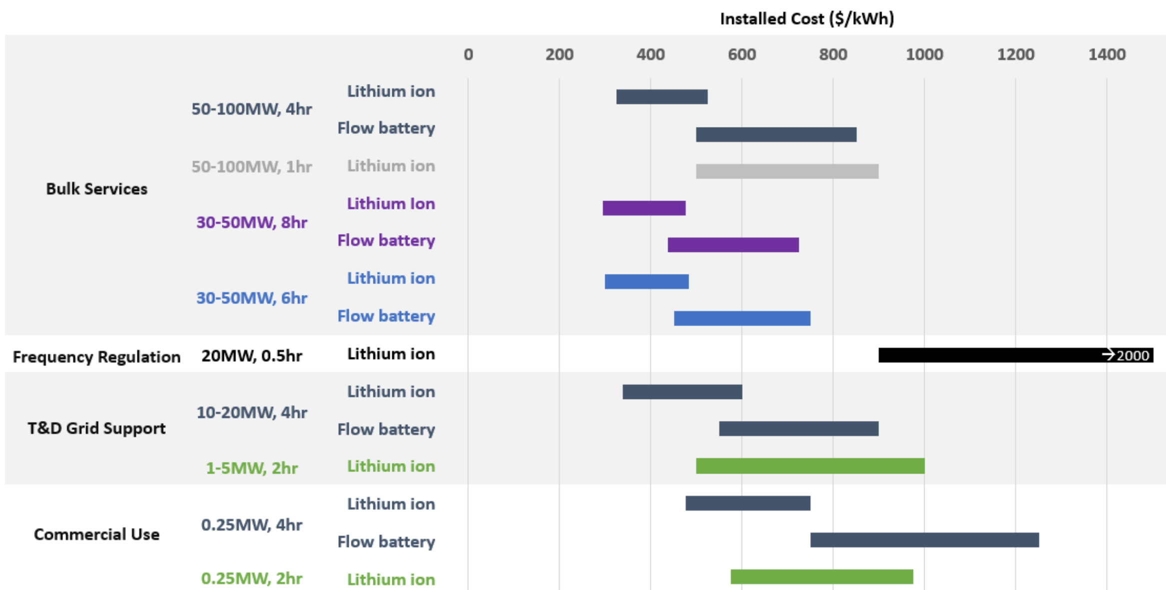


Figure 6-35
Energy storage installed cost summary per unit rated energy capacity, by application, 2019 projections. *Source: EPRI*

Table 6-16
Installed cost for energy storage technologies, by application, 2019 projections. *Source: EPRI*

Application	Technology	Capacity (MW)	Duration (hours)	2019 Cost Range ($/kW)	2019 Cost Range ($/kWh)
Bulk Services	Lithium ion	50-100	4	$1300 - $2100	$325 - $525
	Flow battery	50-100	4	$2000 - $3400	$500 - $850
	Lithium ion	50-100	1	$500 - $900	$500 - $900
	Lithium ion	30-50	8	$2350 - $3800	$295 - $475
	Flow battery	30-50	8	$3500 - $5800	$440 - $725
	Lithium ion	30-50	6	$1800 - $2900	$300 - $485
	Flow battery	30-50	6	$2700 - $4500	$450 - $750
Frequency Regulation	Lithium ion	10-20	0.5	$450 - $1000	$900 - $2000
T&D Grid Support	Lithium ion	10-20	4	$1350 - $2400	$340 - $600
	Flow battery	10-20	4	$2200 - $3600	$550 - $900
	Lithium ion	1-5	2	$1000 - $2000	$500 - $1000
Commercial Use	Lithium ion	0.25	4	$1900 - $3000	$475 - $750
	Flow battery	0.25	4	$3000 - $5000	$750 - $1250
	Lithium ion	0.25	2	$1150 - $1950	$575 - $975

Lithium ion battery systems are projected to remain the lowest cost battery energy storage option for a given site and utility use case. The costs of lithium ion batteries have decreased by roughly 80% since 2010 due to a number of factors. Market demand from transportation and stationary markets have driven increased cell production by manufactures, while efficiencies gained from design and deployment experience have also contributed to the decrease in lithium ion system installed costs. Furthermore, the storage industry as a whole has been able to benefit from cost reductions of Power Conversion system (PCS) and other Balance of Plant (BOP) components.

The range of flow battery installed costs is wider than the lithium ion range (for a system used within a given application). Most flow battery vendors have yet to successfully move beyond demonstration or small commercial projects, and each manufacturer is at a different stage of commercial and design maturity; some larger flow battery systems installed to date are one-off designs, while others are systems based on small modular designs. Finally, most of the systems installed are demonstration projects. Demonstration projects typically incur additional soft costs on top of what suppliers and integrators can provide for commercial projects.

When analyzing the economics of an energy storage facility, it is important to understand not only the upfront installed costs, but also O&M and decommissioning costs. ESS O&M costs partly depend on the application for which the ESS is utilized, as an ESS's life cycle and degradation rate will vary by operating regime. The type of O&M services required will depend on the application and use case of the ESS; likewise, the frequency of O&M service may change depending on the primary and secondary operations of the ESS. Depending on how the system is cycled, its usable operating life could be reduced below expected calendar life.

Additionally, assessing ESS costs should also be done in conjunction with an assessment of the ESS's net market value. Energy storage differs from conventional generation in operating cost and market benefits. The economic analysis of a specific project needs to capture the costs and benefits of charging and discharging, and the multiple services an energy storage facility can provide to the grid and/or customers or end-users.

Lithium Ion Installed Cost Projections

Lithium ion installed costs are projected to continue to decrease through 2030 and potentially beyond. Figure 6-36 shows projected installed cost for front of the meter systems with an upper and lower bound based on both the potential differences in costs due to the specific requirements of a project, scale, and uncertainty in the future market. Cost reductions will likely be accomplished across all major cost categories. Figure 6-37 illustrates an example breakdown of installed cost for a 20MW, 4hr system.

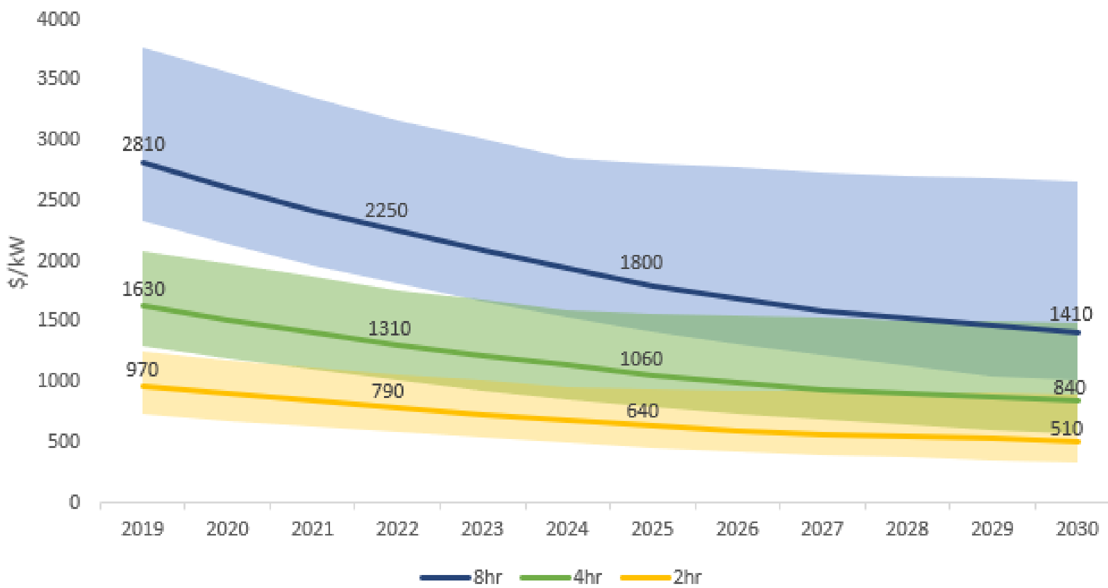


Figure 6-36
Lithium ion installed cost projections, 2019-2030. *Source: EPRI*

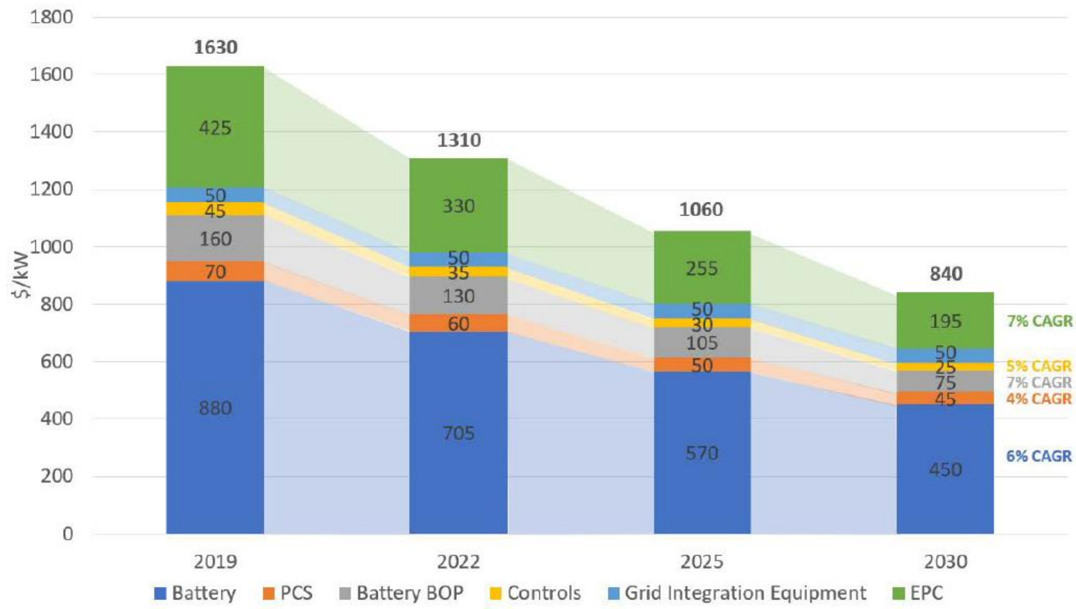


Figure 6-37
Installed costs projections for a 20MW, 4hr lithium ion system, 2019-2030. ***Source: EPRI***

Flow Battery Installed Cost Projections

Figure 6-38 and Figure 6-39 show flow battery cost projections, illustrating the potential range in costs and an example breakdown, respectively. The battery cost estimates are largely based on the then future costs estimated in a 2007 EPRI study of vanadium flow batteries, while the grid integration and EPC costs are assumed to be the same as the lithium ion 2030 projections from this study.[37] Cost projections were not performed for other flow battery chemistries as further research is needed to better understand the various components and cost drivers. Costs presented are not tied to a specific year but characterized simply as future.

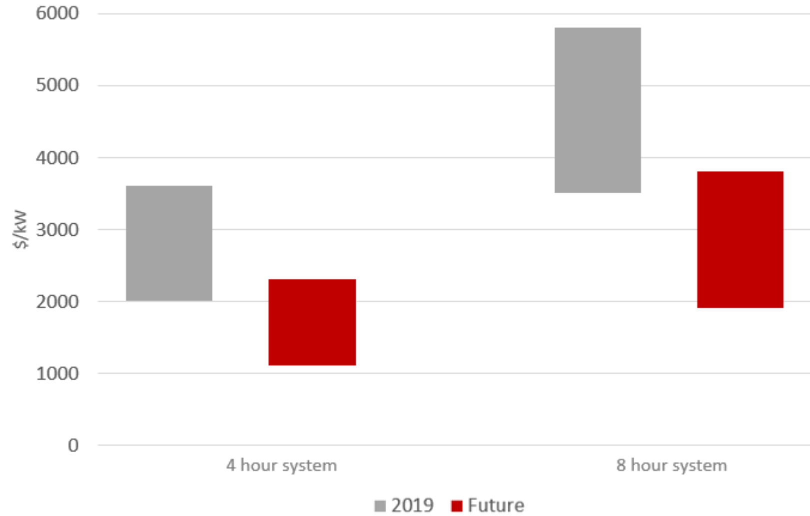
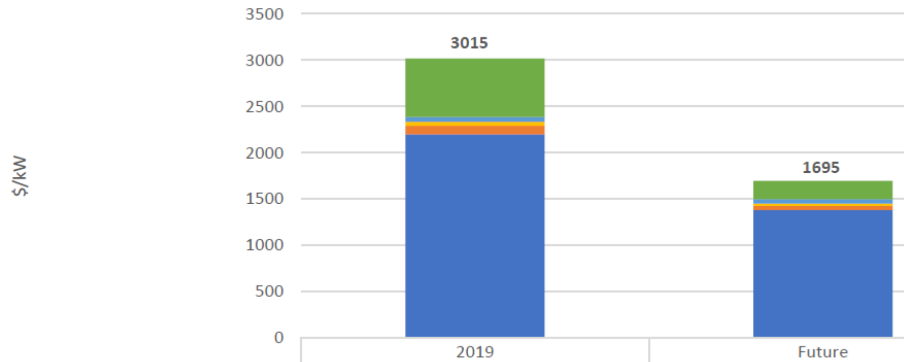


Figure 6-38
Vanadium flow battery installed cost projections. ***Source: EPRI***



	2019	Future
EPC	630	195
Grid Integration Equipment	50	50
Controls	45	25
PCS	90	45
Battery + BOP	2200	1380

Figure 6-39
Installed costs projections for a 20MW, 4hr Vanadium flow battery system, 2019-2030. ***Source: EPRI***

Storage Performance Measurement Findings to Date

The Electric Power Research Institute (EPRI), in collaboration with the U.S. Department of Energy (DOE), has been analyzing fielded energy storage system performance under the Energy Storage Performance and Reliability Data Initiative Supplemental which began in 2018. This effort has allowed improved understanding of true operational performance for a variety of storage technologies and has highlighted data requirements and provided information and algorithms needed to assess performance independently from vendor reported values. EPRI's current Energy Storage Performance and Data Initiative has been collecting data from fielded systems for over three years and has accumulated large of amounts of data (in the TB range) from a variety of Li Ion battery systems and a recently installed Vanadium Redox flow battery. Some of the major lessons learned include:

- Hi-fidelity system monitoring data is often obscured by battery management systems (BMS), used internally for calculation of high-level summary parameters, but inaccessible for independent verification of health metrics by owners or operators. Some systems preclude external access to the data needed to independently assess performance.
- While traditional utility SCADA systems can be tuned to acquire energy storage system data, they are not well suited to capturing granular, higher-frequency data for detailed degradation analysis, event forensics or maintenance.
- Ancillary system malfunctions can greatly impact the overall system reliability. The failure of standard HVAC units has appeared to be the chief contributor to system non-performance. Off the shelf uninterruptible power supply (UPS) systems that provide back up for control systems have also contributed to substantial overall system outages.
- Field response programs designed to allow qualified personnel to rapidly respond to issues or outages are still maturing but lack the required staffing levels, rigor, organization, and success experienced by other industries.

- There is no standard data model for energy storage systems. As a result, the acquisition of data, the ensuing ingestion of that data into EPRI's databases, and automated analysis have proved to be a significant challenge. The standard making process is very lengthy and arduous. Specifications for new systems, can, however, rely on guides to detail the data needed, protocols used to transfer data, and the specifics of data rates (poll frequencies).
- Vendor firmware changes can have significant impacts on the data models, sensor data utilization, and even the absolute values of vendor-calculated and reported metrics.
- Legacy enterprise level Asset Management and Performance Assessment software platforms such as Trouble Management Systems (TMS) are not easily tuned to the nuances of storage.

Conclusions and Future Research Questions

This report provided an overview of different energy storage technologies, grid services, technical attributes, deployment and cost of Lithium ion and flow battery energy storage systems.

As technology and installation costs for ESS continue to decline, new research questions arise in working toward a better understanding of future costs. Among the new questions recently articulated include:

- How will emerging codes and standards such as NFPA 855 and IFC 2021 impact installation costs? The draft standards may impose additional clearance requirements, documentation, testing, monitoring, and other requirements that have the potential to increase EPC costs.
- Will solar plus storage be more cost effective with DC or AC coupled inverters? What conditions influence the costs?
- What new technologies have the potential to be cost competitive with incumbent lithium ion technologies in the near term and in the long term?
- What are the actual labor-hours involved in ESS maintenance? How should utilities assess whether to bring ESS maintenance in-house?
- What are actual augmentation costs and how do they vary based on system configuration?
- What is the current and future status of recycling facilities in North America that can handle materials from lithium ion battery systems and other ESS technologies? Given that the dismantling and recycling cost of an ESS is sensitive to the distance to a dismantling/recycling facility, are there plans to increase the number of recycling facilities and decentralize recycling of spent industrial batteries in North American and elsewhere?
- What is the impact of projected recycling cost in ESS purchase contracts? Which approach is most likely to prevail in purchase contracts: buy-back of valuable components or local recycling/disposal?
- What is the cost of secondary use of vehicular lithium ion batteries for stationary applications? What is the relative cost-benefit equation of using such batteries?

Energy storage performance and cost should continue to be re-evaluated as rapid change is underway in the energy storage sector. New policies and regulations, advances in technology, rapidly falling prices, and growth in variable renewable electricity generation may widen the array of stationary applications being targeted.

Improved Operator Situational Awareness

Changes in the Electrical Energy and Resulting Challenges to Operator Situational Awareness

Recent changes and trends in electrical energy—both on the generation side, with increasing levels of electricity generation from renewable energy sources such as wind and solar, and on the energy consumption side, with new and more efficient consumption technologies—are changing use patterns and dynamical characteristics of the entire infrastructure. The renewable resources, both on the transmission and distribution systems, as well as behind the meters on the end use customer facilities are interconnected using inverters. Several large fossil fuel synchronous generating plants are being decommissioned. Additionally, demand response as a non-wires alternative is also playing increasing significant role in the electrical power systems. All these trends, in not too distant future, will cause significantly higher and faster variations in the system inertia, short circuit currents and transmission loadings, introducing higher levels of variability and uncertainty into power system operation.

Traditional Situational Awareness tools available to system operators in the Energy Management System (EMS) will not be adequate in a stochastic environment with faster dynamics. Multifold growth in small energy resources, increasing automation at a local end user and substation level, FACTs devices, etc. have a potential to create floods of measurements and alarms to the control center. Additionally, need for monitoring physical and cyber security, communication and data networks will further complicate the complexities of operations. Developing tools to perform system security analysis and based on that provide integrated decision support solutions using cognitive systems engineering to the system operators will be necessary. This section discusses some of the Advanced Situational Awareness Tools in various stages of technology readiness being developed to meet the future needs.

Situational Awareness in the EMS context is to appraise current state of the grid and accurately anticipate changes in the states in real-time operation's time horizon considering all probable contingencies to enable effective operator actions to preserve utmost reliability. There are two aspects to this; (1) determining current and near-future states and their adequacy for reliable operation, and (2) present this information to the operators, and alert them when needed, unambiguously using appropriate cognitive visualizations. This discussion, based on the working group priorities, primarily addresses the tools being introduced for the assessment of system states in the real-time operation's time frame.

High Resolution Monitoring using Synchrophasors and Applications using them [1]

With the advent of deployment of PMUs on transmission systems providing high resolution (usually 30 reports/second) synchrophasor measurements provides granularity of observability to monitor system dynamics that was not possible with SCADA measurements (typically reported every 2-4 seconds). Some of the synchrophasor applications are discussed below:

Wide Area Monitoring Displays (WAMD)

These displays provide grid's operating conditions, through the visualization of time-aligned real-time synchrophasor measurements (voltage magnitudes, phase angles etc.) on geographical layered displays. Many of these tools have playback capabilities, can provide alerts (e.g. voltage magnitude violations, large voltage phasor angles, etc.), and some have diagnostic capabilities (e.g. grid stress index based on phase angle differences).

Phasor angle polar plot provide system stress level. Also if an island is formed, voltage phasor from the islanded area with a different frequency would be rotating with respect to the other phasors.

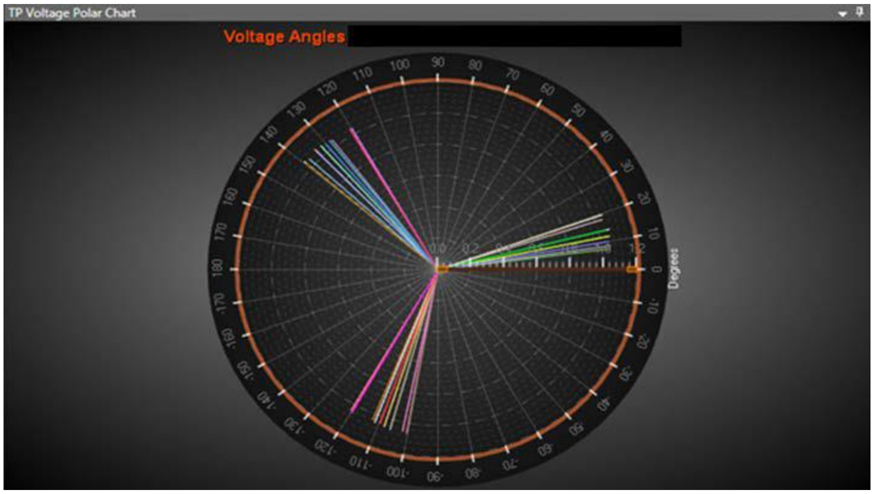


Figure 6-40
Display of voltage phase angles (Dominion)

Figure 6-41
Visualization of wide area phase angles using RTDMS (ERCOT)

Several vendor tools with WAMD functionalities are available in the market, and several US utilities/ISOs/RCs as well as international utilities are using those in their operations (usually testing or production environment).

The table below illustrates the mapping of utilities/ISOs/RCs to this application along with associated tools being used.

US ISOs/RCs	Tool Name	endor
ERCOT	RTDMS	EPG
NYISO	RTDMS	EPG
Peak Reliability	PI-ESRI	OSIsoft-ESRI
US Utilities	**Tool Name**	**Vendor**
ATC	PhasorPoint	GE
BPA	PI ProcessBook	OSIsoft
Dominion Virginia Power	RTDMS	EPG
Duke Energy	RTDMS	EPG
Florida Power and Light	PhasorPoint	GE
Maui Electric	SynchroWAVe Central	SEL
OG&E	PhasorView	In-house
PG&E	SynchroWAVe Central PhasorPoint	SEL GE
SCE	Synchronized Measurement & Analysis in Real-Time (SMART)	In-house
SDG&E	PI ProcessBook SynchroWAVe Central	OSIsoft SEL
International	**Tool Name**	**Vendor**
AESO (Canada)	PhasorPoint OpenPDC	GE GPA
APG (Austria)	SynchroWAVe Central	SEL
Ceming Utility (Brazil)	Phasor Synchronized Measurement System (SISMEF) OpenPDC	In-house GPA
FINGRID (Finland)	PI ProcessBook	OSIsoft
Hydro-Québec (Canada)	Wide-Area Situational Awareness (WASA)	In-house
POSOCO (India)	SynchroWAVe Central	SEL
SP Energy Networks (UK)	VISOR	In-house
TenneT (Germany)	N/A	In-house
TERNA (Italy)	WebWAMS	In-house
XM (Colombia)	Intelligent Supervision and Advanced Control System (iSAAC)	In-house

State Estimation using Synchrophasor Measurements

State Estimation (SE) is an essential tool used for Situational Awareness. The introduction and the continuously growing installations of PMUs enable more efficient and accurate monitoring of the power system through advanced SE that uses synchrophasor measurements. A hybrid SE utilizes both SCADA measurements and synchrophasors. SE can be also performed by using only synchrophasors, which is typically referred to as linear state estimation (LSE).

The following table illustrates utilities/ISOs/RCs that have implemented synchrophasor-based SE along with the associated tools being used.

ISOs/RCs/Utilities Using Synchrophasor-Based State Estimation. US ISOs/RCs	Tool Name	Developed by
NYISO	Phasor Enhanced State Estimator	ABB
Peak Reliability	enhanced LSE (eLSE)	EPG
PJM	enhanced LSE (eLSE)	EPG
US Utilities	**Tool Name**	**Developed by**
BPA	enhanced LSE (eLSE) EMS	EPG Alstom/GE
Dominion Virginia Power	OpenECA	GPA
Duke Energy	EMS	Alstom/GE
SCE	enhanced LSE (eLSE)	EPG
International	**Tool Name**	**Developed by**
XM (Colombia)	Intelligent Supervision and Advanced Control System (iSAAC)	In-house

Oscillation Detection

High-resolution time synchronized measurements available from PMUs on wide area of an interconnection make it possible to detect oscillation modes, their damping and mode shapes. Several signal analysis tools for oscillation monitoring using synchrophasor measurements have been developed and continue to be refined for dynamic analysis. Some of the methods used in the tools are Fourier spectral analysis, Prony Analysis and Parametric Ringdown Analysis. Ringdown signals, like those resulting from disturbances, usually have high signal to noise ratio, and would provide richer data for analysis. Ambient data on the other hand is more difficult to analyze because of much lower signal to noise ratio. Forced oscillations is a special category of oscillatory behavior and development of modal analysis and oscillation source detection algorithms for forced oscillations is an ongoing research activity. The following table summarizes several utilities/ISOs/RCs that are using oscillations detection tools along with the associated vendor tools.

ISOs/RCs/Utilities Using Synchrophasor-Based Oscillation Detection Applications. US ISOs/RCs	Tool Name	Developed by
ERCOT	RTDMS	EPG
ISO-NE	PhasorPoint Oscillation Source Location (OSL) Tool	GE In-house
NYISO	RTDMS	EPG
Peak Reliability	PhasorPoint (Peak's own server) Modal Analysis Software (MAS) Oscillation Monitoring System (OMS) PI ProcessBook	GE Montana Tech. WSU OSIsoft
PJM	RTDMS	EPG
US Utilities	**Tool Name**	**Developed by**
BPA	Oscillation Detection (OD)	In-house
Dominion Virginia Power	RTDMS	EPG
Duke Energy	RTDMS	EPG
SDG&E	SynchroWAVe Central	SEL
SRP	SynchroWAVe Central	SEL
International	**Tool Name**	**Developed by**
AESO (Canada)	PhasorPoint	GE
FINGRID (Finland)	N/A	In-house
Manitoba Hydro (Canada)	PhasorPoint	GE
POSOCO (India)	Oscillation Monitoring System (OMS)	In-house
Swissgrid (Switzerland)	Power Oscillation Monitoring (POM) & Power Damping Monitoring (PDM)	In-house (with ABB)
TenneT (Germany)	N/A	In-house
XM (Colombia)	PhasorPoint Siguard	GE Siemens PTI

EPRI has also developed adaptive oscillation damping controller to improve damping of known oscillatory modes that is going through hardware in the loop testing, as a final step before field installation.

Voltage Stability Monitoring

Voltage stability analysis (VSA), and any operational limits resulting from it is traditionally derived from model-based simulation tools. Several online measurement-based voltage stability analysis tools have been proposed using synchrophasor data. The majority of them are based on developing a Thevenin Equivalent using the measured data, and using it to determine stability margins, similar to those provided by the P-V curves. Some methods determine sensitivities using synchrophasor measurements, which are somewhat more accurate, since the measurements do reflect actual load behavior. A few methods have also used Lyapunov Exponent Methods to assess voltage stability. Of course, an application detecting instability after system becomes unstable, would be of little use if there is not sufficient time to deploy effective mitigation measures. Hence most tools attempt to provide trends and margins. The main disadvantage though of the measurement-based tools is that they provide VSA analysis based on the system's operating condition and cannot predict voltage stability margins for potential contingencies. The following table lists several users, and the tools they have incorporated in operation.

ISOs/RCs/Utilities Using Synchrophasor-Based Voltage Stability Monitoring Applications. US ISOs/RCs	**Tool Name**	**Developed by**
ISO-NE	Region of Stability Existence (ROSE)	V&R Energy
NYISO	EMS-based Phasor Enhanced Voltage Stability Monitor	ABB
Peak Reliability	ROSE	V&R Energy
US Utilities	**Tool Name**	**Developed by**
BPA	Measurement-Based Voltage Stability	In-house
Entergy	Measurement-Based Voltage Stability Assessment	EPRI
PG&E	Real Time Voltage Instability Indicator (RTVII)	Quanta Technology
SCE	RTVII (standalone)	Quanta Technology
International	**Tool Name**	**Developed by**
Ceming Utility (Brazil)	Phasor Synchronized Measurement System (SISMEF)	In-house

Other Miscellaneous Uses of Synchrophasor Measurements in Operations

Synchrophasor measurements are also being used to determine angle across open breaker to help operators make decisions on reclosing. Several applications also have events replay capability, that uses measurements from short-term archival system for operators to be able to replay a disturbance scenario to improve understanding of the disturbance and provide better decision support.

Dynamic Security Assessment [2]

Traditionally, real-time contingency analysis (RTCA) is performed using steady-state analysis, to assess if the system in current operating conditions will end up in a new acceptable steady state following contingencies. This is called static security assessment (SSA). However, this does not provide assessment of the system during the transition phase during and immediately following a disturbance. Dynamics analysis conducted to evaluate system dynamic performance during and immediately following the disturbance is called dynamic security assessment (DSA).

DSA has been defined by the Institute of Electrical and Electronics Engineers (IEEE), Power Engineering Society's (PES), working group on DSA as Dynamic Security Assessment is an evaluation of the ability of a certain power system to withstand a defined set of contingencies and to survive the transition to an acceptable steady-state condition.

Most of the DSA consists of an offline analysis of various criteria disturbances by taking state estimation (SE) solution as a starting steady state condition. For transient stability analysis this entails taking solved powerflow solution from SE, linking dynamics data, and then running all the disturbances. In most cases, multiple processors are used to run all the disturbance simulations in a few minutes, and compiling results of those simulations to provide to system operators. Similarly, PV analysis is performed to provide power transfer limits over a specific transmission path using SE solution as a starting point.

Since DSA analysis for a large control area takes several minutes (10-15 min. for transient stability analysis and 5 min. for Voltage Stability power transfer limits), several researchers are investigating for online DSA using AI methods.

Improved Forecasts

With increasing penetration of distributed renewable resources on the system, as well as increased use of demand response and resulting fast changing system operating conditions, improved short term (near term) forecast of system loads, renewable generations, available demand response on a local area basis would be essential for improved security assessment and situational awareness.

Several AI based short term load forecast tools are already used by many utilities. Several venders also provide solar irradiance and PV power forecasts (e.g. steadysun, solcast).

PJM has a tool developed inhouse that would provide data on available demand response in an area of interest.

Improved Analytics

With large numbers of resources, and the availability of resources changing all the time, increased deployment of smart end use devices, electric vehicles, etc. will (1) increase volumes of monitored data (especially as higher resolution monitoring is deployed), and (2) computational complexities for state estimation, security analysis and fast contingency selection and analysis for it, optimization, and voltage control. So faster processing, parallelization of solutions, improved solution techniques, model accuracies and management will be essential. Post processing of various analysis results to provide an operator an integrated decision support dashboard display will also be required. And suggested operator intervention actions for most effective control actions when security threats are identified would also be required.

State of the EMS

As system control becomes more complex, and physical and cyber securities also become a factor to address, monitoring the integrity and accuracy of monitored data streams, proper functioning of all the analysis tools and trustworthiness of analysis results would be essential.

Transformer Monitoring

Large substation transformers that interconnect different voltage levels of the grid are major capital assets that are essential to the reliable delivery of economic power. Transformers can also perform a critical role in supporting utility efforts to increase power flows through existing transmission corridors to optimize grid utilization.

Given the importance of transformers in a power system—and their high cost and long lead time for replacement—managing transformer fleets to maintain high levels of health and performance presents ongoing challenges for utilities striving to employ their assets to the fullest extent possible while maintaining system reliability and controlling costs.

The challenges are compounded by transformer demographics. A high percentage of installed transformers are approaching or have exceeded their 40 year design lives. Replacing large numbers of these aging assets is neither practical nor financially feasible, so utilities seek to get as much performance and remaining life as possible from their transformer fleets.

System abnormalities, loading, switching, and ambient conditions normally contribute to transformer accelerated aging and sudden failure. Therefore, central to transformer management is effective monitoring to gain a comprehensive view of transformer health, which can help utilities assess equipment condition, diagnose incipient degradation, anticipate problems, prevent failures and extend transformer life.

Provided results are properly interpreted, monitoring offers intelligence to support repair/refurbish/ replace decisions that maximize performance and minimize costs. In short, monitoring can help utilities ensure that transformers stay healthy and perform critical functions such as supporting sustained additional loads, and not be the weak links in the power delivery chain.

Technology Overview

Transformer monitoring technology offers numerous opportunities to deliver value to utilities and stakeholders:

Safety and Reliability: Knowledge of whether a transformer is in imminent risk of failure will enable actions to be taken to address the safety of utility personnel.

Condition-Based Maintenance: Maintenance actions can be initiated at appropriate times increasing cost effectiveness.

Asset Management: Sensors will enable improved allocation of resources for asset management. Sensor data is used together with similar vintage performance information, failure databases, and operational data.

Increased Asset Utilization: Improved dynamic ratings may be achieved if more precise, real-time knowledge of the components' condition can be obtained from sensors.

Forensic and Diagnostic Analysis: Investigating teams will have better information to understand root causes of failures.

Increased Operator Awareness: Operators will be able to make more informed decisions that account for high-risk components.

Workforce Deployment: Personnel can be deployed in a planned manner to address either an imminent outage or possibly prevent an outage.

Substation transformers are large and complex assets that offer many parameters that can be monitored to identify underlying failure modes and degradation. Numerous sensors have been developed to measure these parameters. Commonly applied transformer monitoring technologies are as follows:

1. Transformer load monitoring
2. Transformer top-oil (and possibly bottom oil) monitoring
3. Transformer hot-spot monitoring
4. Dissolved Gas Analysis (DGA) monitoring
5. Transformer bushing monitoring
6. Partial discharge monitoring
7. Moisture in oil
8. Transformer vibration (and possibly ballistic impact) monitoring
9. Measurement of Geomagnetically Induced Currents (GICs)

Application Considerations

Algorithm Development and Analysis. Monitors, by themselves, only measure data. The conversion of that data into information and the extraction of applicable knowledge provides the decision support mechanisms to prioritize maintenance, replacement and inform other asset management actions. Algorithms should be developed to convert data measured by many monitor types into actionable information.

Data Integration and Visualization. Integrating sensor data into the utility information and communication infrastructure is essential to ensure that the correct information is provided in an appropriate format to each of the stakeholders.

Power Harvesting and Storage. In some instances, sensors need to be deployed in areas where power is not readily available (e.g. on a phase conductor). Power harvesting and storage technologies are then an important application consideration.

Communications. The last link between the sensor and the utility communication infrastructure is often a challenge.

Application considerations can be further explored by considering each common monitor in turn:

Transformer Monitor	Application consideration
Transformer load monitoring	Typically factory installed so application considerations are only the integration of these signals into the utility monitoring infrastructure
Transformer top-oil (and possibly bottom oil) monitoring	
Transformer hot-spot monitoring	Hot-spot sensors that are placed into the transformer windings are fiberoptic sensors and are fitted during manufacture of the transformer. Application considerations are how to integrate the data from the fiberoptic interrogation unit into the utility monitoring infrastructure.
Dissolved Gas Analysis (DGA) monitoring	DGA monitors can monitor multiple gasses or a smaller subset of gasses. The first application consideration is thus how many gasses to monitor. This decision is based on the criticality of the transformer since a higher monitor cost is associated with monitoring more gasses. The second application consideration is which DGA technology to apply. This decision impacts both maintenance costs and the accuracy of the on-line DGA results.
Transformer bushing monitoring	Bushing monitors attach to a tap point on the bushing to track parameters such as power factor, capacitance and partial discharge. A primary application consideration is whether the bushing has such a tap point.
Partial discharge monitoring	Partial discharge (PD) monitoring in transformers is most commonly performed using the following three approaches: Firstly PD monitoring via an on-line bushing monitor. Secondly PD monitoring via a UHF (Ultra High Frequency) coupler fitted to the tank or inserted in a drain valve and thirdly, AE (Acoustic Emission) attached to the external tank of the transformer. The application of PD is most often driven by known issue that has been identified in a transformer (for example by an elevated DGA reading).
Moisture in oil	Application considerations for on-line moisture in oil monitoring are most often driven by the need for either tracking transformer ageing (which is strongly accelerated by moisture) or tracking of moisture to guide transformer overloading decisions (since high moisture can cause premature failure during high loading).
Transformer vibration (and possibly ballistic impact) monitoring	Application of vibration monitoring on transformers is commonly constrained to those transformer designs with known vibration issues – or those transformers where utilities are interest in relating GIC levels to tank vibration. Application of ballistic monitoring (using vibration) is commonly driven by historical challenges with specific transformers in specific locations.
Measurement of Geomagnetically Induced Currents (GICs)	The application of monitoring for Geomagnetically Induced Currents (GICs) is directed at large power transformers on the bulk power network.

Readiness of Monitoring Technologies

The readiness of each of the commonly applied monitoring technologies is described below.

Transformer Monitor	Readiness	Comments
Transformer load monitoring	Ready today	Commonly applied
Transformer top-oil (and possibly bottom oil) monitoring		
Transformer hot-spot monitoring	Ready today	The fiberoptic monitoring within the windings is typically only deployed in large, critical units. For the remainder of the monitoring an estimation of the hot-spot is made using a combination of the top-oil temperature and the loading
Dissolved Gas Analysis (DGA) monitoring	Ready today	DGA monitoring uses many different technologies (e.g. gas chromatography, Photoacoustics etc.). Each technology has a different length of proven field experience.
Transformer bushing monitoring	Ready today	On-line bushing monitoring technologies using a variety of approaches (absolute method, balance method etc.) are available.
Partial discharge monitoring	Ready today. Technologies emerging	PD monitoring using bushing monitoring, UHF and AE are available. AE monitoring is more commonly applied in short-term investigations than in continuous on-line monitoring
Moisture in oil	Ready today	A range of commercial solutions are available for-on-line moisture monitoring. Some monitors also include temperature monitoring in the same probe.
Transformer vibration (and possibly ballistic impact) monitoring	Ready today. Technologies emerging	Transformer vibration or ballistic monitoring is available today. Ballistic monitoring on transformer tanks is less common than vibration monitoring – but remains an emerging field.
Measurement of Geomagnetically Induced Currents (GICs)	Ready today. Technologies emerging	GIC monitoring solutions on the grounded neutral of transformers are available. Less common are solutions that measure the GICs on the phase conductors. (EPRI has developed a radio frequency sensor to measure GIC from solar storms in transfomers and lines. This sensor connects to the energized phase conductors. Several sensors have been installed at utility sites and GIC activity has been observed)

On the research front, to meet needs for improved transformer diagnostics and condition assessment technologies, EPRI is developing a series of transformer monitors that:

- Measure parameters relevant to underlying failure modes and degradation
- Are mechanically designed for easy installation
- Power harvest or use battery power for more than a decade of battery life
- Contain embedded algorithms to translate measured data to applicable metrics
- Can provide raw data on request (depending on monitor type)

EPRI RF monitors include Acoustic Emission, UHF, tank vibration, ballistic impact and GICs on both phase and grounded neutral conductors. An overview of the EPRI RF Monitor Suite is shown in Figure 6-42.

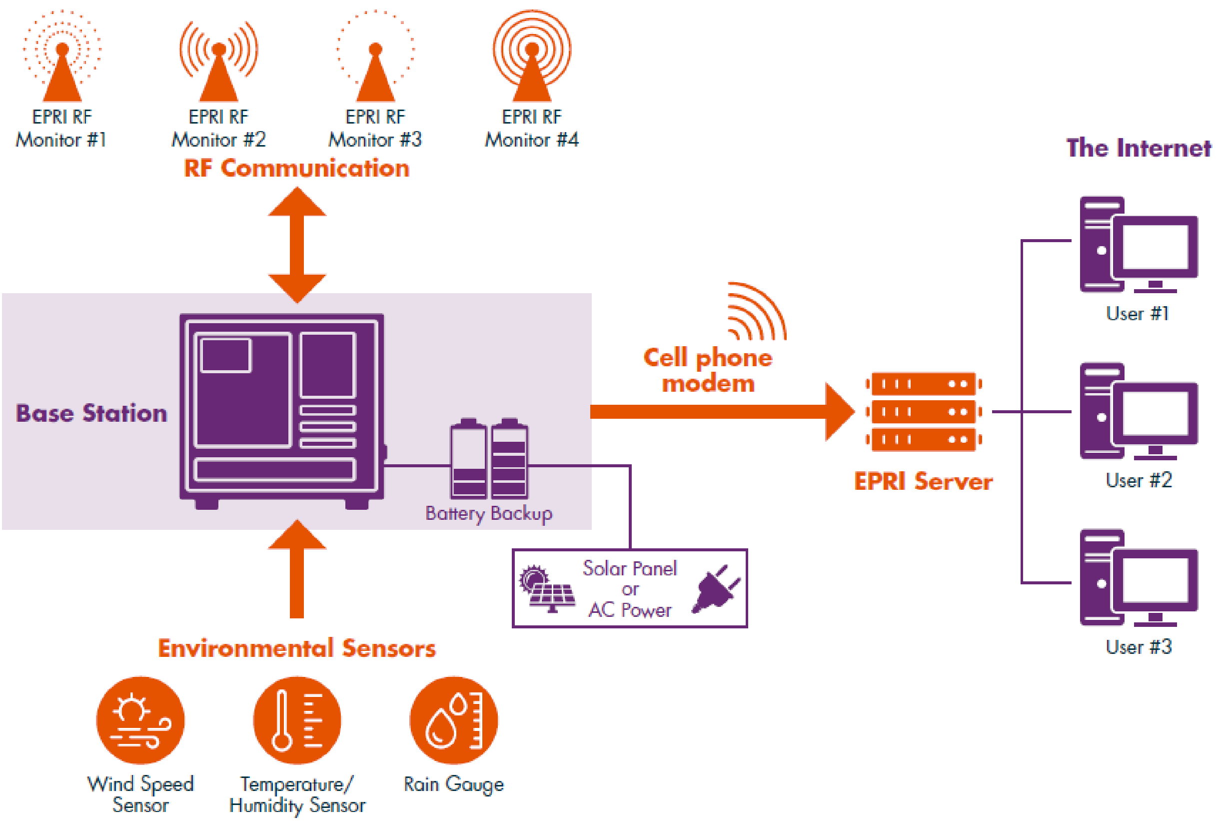


Figure 6-42
EPRI RF Monitor Suite: Multiple monitors communicate with a base station that aggregates, stores, and transmits data to EPRI servers or utility asset health systems.

Field or Testing Results

For new and emerging transformer monitoring technologies, testing prior to broad-scale deployment is common. Sometimes an individual utility will try new technologies on their own system, but more common nowadays is collaborative testing in a research substation - since it allows for much wider flexibility in evaluation. EPRI has build a 138kV research substation to meet this industry need for testing (See Figure 6-43). In this research substation EPRI is evaluating for the industry a wide range of transformer on-line monitors, including the EPRI developments of wireless RF monitors for transformers. EPRI also conducts field demonstrations with members to ensure that the monitors reliably provide actionable information. These demonstrations enable the continued refinement and improvement of the technology.

Figure 6-43
EPRI's full-scale 138kV research substation for industry testing of transformer monitors

Vendor Landscape

The vendor landscape for transformer monitoring is very wide, but a list of vendors (albeit incomplete) would include ABB, Siemens, GE, Qualitrol. DOBLE, ZTZ, EPRI, MISTRAS, Vaisala, Serveron, Lumasense, Dynamic Ratings, Reinhausen, Weidmann, Power Diagnostics Systems, Omicron, Camlin etc.

Advanced High-Temperature, Low Sag (HTLS) Conductors

Introduction

More than 80% of bare stranded overhead conductors used in transmission lines consist of a combination of 1350-H19 (nearly pure aluminum, 1350, drawn to the highest temper possible—H19) wires, stranded in one or more helical layers around a core consisting of one or more steel strands. The steel strands are coated by one of several different methods to resist corrosion. By varying the size of the steel core while keeping the cross-sectional area of aluminum constant, the composite tensile strength of ACSR conductors can be varied over a range of 3 to 1.

The mechanical and electrical properties of ACSR (and all aluminum conductors, such as AAC, AAAC, and ACAR) are quite stable with time, as long as the temperature of the aluminum strands remains less than 100°C. Above 100°C, the work-hardened aluminum strands lose tensile strength with time at an increasing rate with temperature. The steel core strands, however, are unaffected by operation at temperatures up to at least 300°C (although conventional "hot-dip" galvanizing may be damaged by prolonged exposure to temperatures above 200°C).

The sag-temperature behavior of ACSR is also dependent on the size of the steel core. At moderate to low conductor temperatures, the thermal elongation rate of ACSR is between that of steel (11.5 micro strain per °C) and that of aluminum (23 micro strain per °C). For example, with Drake ACSR, the thermal elongation is 18.9 micro strain per °C up to a temperature about 70°C, but decreases to the thermal elongation rate of the steel core alone (11.5 micro strain per °C) at higher temperatures.

HTLS conductors are able to operate continuously at temperatures above 100°C (the HT part) without any reduction in breaking strength. In addition, they exhibit thermal elongation rates that are less than ACSR (the LS part). This characteristic allows the HTLS conductor to sag less than a conventional ACSR conductor at any temperature, especially elevated temperatures.

Technology Overview

HTLS Conductors—How They Work

As noted previously, the acronym HTLS stands for "high-temperature low-sag" conductors. The name summarizes the key properties of the conductors: They can be operated at high temperatures (above 100°C) for extended time periods without losing tensile strength or otherwise deteriorating mechanically, electrically, or chemically, and they elongate less with temperature than normal all-aluminum or steel-cored aluminum conductors.

In addition to these properties, which are related to the maximum conductor temperature, HTLS conductors must also display the following desirable properties associated with conventional transmission conductors:

- ***Mechanical properties*** — low weight per unit length, high elastic modulus, and low plastic elongation under high mechanical loading to so existing lines can be reconductored with a minimum of structure modification yet remain mechanically reliable.
- ***Robust handling characteristics*** — HTLS conductors must be easily installed and terminated using methods familiar to existing experienced contractors.
- ***Chemical properties*** — resistant to corrosion over lifetimes of 40 years or more; insensitive to ultraviolet aging in the presence of sunlight and ozone.
- ***Low electrical resistance*** — exhibit composite resistance less than or equal to the original conductors with the same diameter.

HTLS Current-Carrying Wire Materials

As with ACSR, HTLS conductors normally consist of two types of component wires. The highly conducting aluminum wires in the outer layers carry most of the electrical current and have conductivity of 61 to 63% International Annealed Copper Standard (IACS; annealed copper is 100% IACS), which is comparable to the 1350-H19 aluminum wires used in ACSR. The core wires of HTLS conductors provide mechanical reinforcement, limiting the elongation of the conductor under high ice and wind loads and at high temperatures. Secondarily, depending on the HTLS conductor design, the outer layers of aluminum wires may contribute to the mechanical behavior of the conductor and the core may carry some portion of the electrical current, but these are not their primary functions.

For HTLS conductors with annealed aluminum strands, the conductor stiffness and breaking strength are largely determined by the core. For HTLS conductors with zirconium aluminum strands, the composite conductor strength and stiffness depend on both the reinforcing core and the aluminum strand layers.

With the exception of the carbon fiber composite core conductors, the various aluminum alloys and the reinforcing materials are normally in wire form, with a wire diameter of the order of 0.1 to 0.2 in. (2.5 to 5 mm). In certain designs, the aluminum wires are provided with a trapezoidal cross section to maximize the aluminum area for a given conductor diameter. The reinforcing core wires are typically round. The properties of the wires vary with wire diameter. Generally, the smaller the diameter to which the wire is drawn, the more work hardening is done, and the higher its tensile strength (although such variations with wire diameter are typically modest).

Current-Carrying Wires

As shown in Table 6-17, the current-carrying wires used in HTLS conductors are capable of continuous operation at temperatures in excess of 100°C with stable electrical and mechanical properties. For example, annealed aluminum strands can be run continuously at 300°C without any deterioration in conductivity or changing tensile properties.

In contrast to ordinary 1350-H19 aluminum, TAL and ZTAL aluminum can be operated continuously at 150°C and 210°C, respectively, without any loss of tensile strength. These aluminum wires have approximately the same electrical conductivity as 1350-H19.

The thermal elongation of all these aluminum wires is comparable and approximately equal to that of 1350-H19 aluminum wires.

Mechanically, the aluminum wires in Table 6-17 are dramatically different. The yield strength of 1350-H19 and the zirconium alloy wires is about 15,000 psi (103 MPa), whereas the yield strength of annealed aluminum wire is about 5000 psi (34 MPa). Thus, high-tension loading events cause relatively large permanent elongation of annealed aluminum wires and result in "loose" strands in composite HTLS conductors that use annealed aluminum wires.

Table 6-17
Characteristics of aluminum and aluminum alloy wires

Type of Aluminum		Minimum Conductivity (%IACS)	Tensile Strength (Mpa) (kpsi)	Allowable Operating Temperature (°C)	
				Continuous	Emergency
Hard-drawn 1350 aluminum	1350-H19 (HAL)	61.2	159–200 23–29	90*	125*
Thermal-resistant zirconium aluminum	TAL	60	159–176 23–26	150	180
Extra–thermal-resistant zirconium aluminum	ZTAL	60	159–176 23–26	210	240
Fully annealed 1350 aluminum	1350-0	61.8**	59–97 8.5–14	350	350

* Manufacturers often suggest performing rating calculations at 75°C/100°C.
** Typical conductivity for annealed aluminum is 63.0%.

Reinforcing Core Wires

A variety of reinforcing core wires is used in HTLS conductors. The core wire materials shown in Table 6-18 include high-strength carbon steel, nickel-alloy Invar steel, aluminum-clad steel, carbon-fiber–reinforced resin composite, and ceramic-fiber–reinforced aluminum.

The three-reinforcing core steel wire types described in Table 6-18 have a similar modulus, but the tensile strength of extra–high-strength and ultra–high-strength steel core wires is 10% and 30% higher, respectively, than high-strength (HS) steel. All have the same thermal elongation coefficient of 11.5×10^{-6}.

The ACCC composite core has a very high tensile strength (60% higher than galvanized HS steel) but a relatively low modulus (about half that of galvanized HS steel). It also has the lowest thermal elongation rate at 1.6×10^{-6}. Its minimum elongation at tensile failure (2%) is a bit less than that of steel (3%).

The ACCR composite core has nearly the tensile strength of steel, but it breaks at a much lower elongation (0.64%). Its thermal elongation rate is 6×10^{-6}, about half that of galvanized steel wire.

Invar steel wire has the lowest tensile strength in the table, but also has the second lowest rate of thermal elongation (3×10^{-6}).

Table 6-18
Characteristics of reinforcing core materials

Core Material	Min. Tensile Strength (kpsi)	Modulus of Elasticity (Mpsi)	Min. elongation at tensile failure %	Coef. of Linear Elong. (× 10-6) per °C	Allowable Operating Temperature (°C)	
					Continuous	Emergency
A Galv. Steel Zn-5Al Steel(B802)	200–210	30	3.0–4.0	11.5	180 250	200 350
A Galv. HS (B606) Zn-5Al EHS (B803)	220–235	30	3.0–3.5	11.5	180 250	200 350
A Galv. UHS Zn-5Al UHS	265–285	30	3.0–3.5	11.5	180 250	200 350
CTC Carbon Fiber composite core	310–360	16.5	2.0	1.6	180	200
3M Ceramic Fiber reinforced aluminum	200	32	0.64	6	250	300
Alum Clad (AW) 20.3% I.A.C.S.	149–195	22	3	13.0	150	200
Galv/AW Invar Alloy	149–157	/22	3	3.2/3.7	180/210	200/240

Note: 1 kpsi = 6.895 MPa; 1 Mpsi = 6.895 GPa.

More information on HTLS conductors can be found in, Guide for Selection and Application of High-Temperature Conductors: 2019 Update. EPRI, Palo Alto, CA: 2019. 3002015651.

EPRI Evaluation

HTLS conductors which have been tested by EPRI include the following:

- ***ACSS and ACSS/TW*** **—** Aluminum Conductor Steel Supported/Trapezoidal Wire—annealed aluminum strands over a conventional steel stranded core; operation to 250°C.
- ***G(Z)TACSR*** **—** Gap-type Aluminum Conductor Steel Reinforced with TAL (Thermal Resistant Aluminum) or ZTAL (Super Thermal Resistant Aluminum), good for continuous operation at 150°C or 210°C, respectively.
- ***(Z)TACIR*** **—** (Super) Thermal Resistant Aluminum Conductor, Invar Steel Reinforced. Operation up to 210°C.
- ***ACCR*** **—** Aluminum Conductor Composite Reinforced—Super Thermal Resistant Aluminum (ZTAL) or annealed aluminum over a composite core made from alumina fibers embedded in a matrix of pure aluminum; operation to 210°C continuous and 240°C emergency.
- ***ACCC*** **—** Aluminum Conductor Composite Core—Fully annealed aluminum helically stranded around a hybrid polymer matrix composite core with both carbon and glass fibers; continuous operation to 180°C.
- ***HVCRC/TW*** **—** High Voltage Composite Reinforced Conductor/ Trapezoidal Wire—fully annealed aluminum helically stranded around a hybrid polymer matrix composite core with both carbon and glass fibers; continuous operation to 150°C.
- ***Lo-Sag by Nexans*** **—** fully annealed aluminum helically stranded around a hybrid polymer matrix composite carbon core. The composite core is sheathed in a plastic sleeve, and both the core and plastic sleeve are in-sheathed by a layer of aluminum foil. Continuous operation to 180°C.
- ***C^7 by Southwire*** **—** Either fully annealed aluminum or aluminum zirconium helically stranded around a seven strand hybrid polymer matrix composite carbon core. The carbon core is protected by a thin Polyether ether ketone (PEEK) layer. Continuous operation to 180°C.

Images of these conductors are shown in Table 6-19.

Table 6-19
HTLS conductors studied by EPRI

Conductor Name (Manufacturer)	Image
ACSS/TW (Southwire)	
G(Z)TACSR (J-Power)	

Table 6-19 (continued)
HTLS conductors studied by EPRI

(Z)TACIR (LS Cables)	
ACCR (3M)	

Table 6-19 (continued)
HTLS conductors studied by EPRI

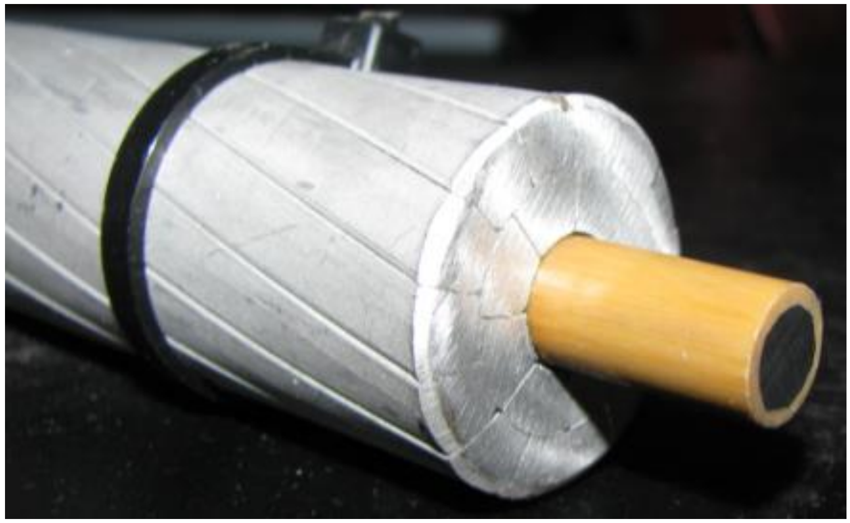
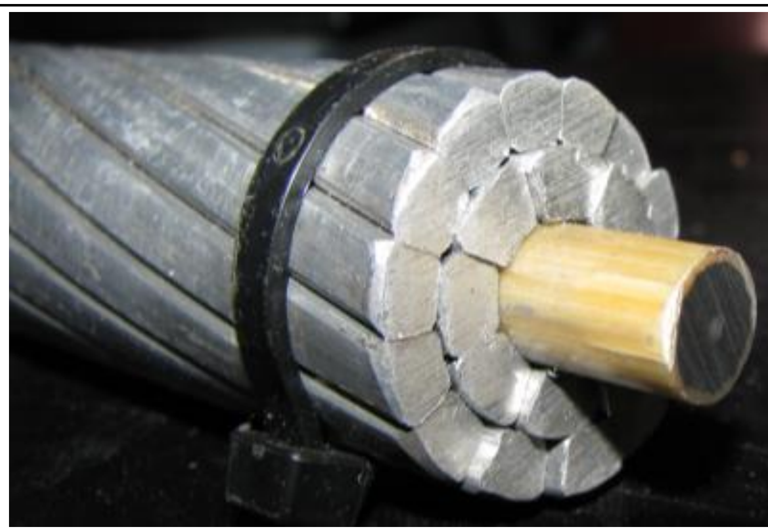
Conductor Name (Manufacturer)	Image
ACCC (CTC Global)	
HVCRC (Mercury Cable)	

Table 6-19 (continued)
HTLS conductors studied by EPRI

Conductor Name (Manufacturer)	Image
Lo-Sag (Nexans)	
C[7] (Southwire)	

The operating temperature limit of a HTLS conductor is a complex combination of the properties of the outer layers of aluminum strands and the reinforcing core. Operating temperature limits for ACSR and for HTLS with high-temperature zirconium alloy aluminum are normally determined by loss of tensile strength in the aluminum. HTLS conductors with annealed aluminum wires can be determined by damage to the reinforcing core. In all cases, the temperature limitation may also be determined by possible deterioration of the connectors and hardware. Therefore, operating temperature limits for HTLS conductors are normally less than or equal to the operating temperature limits of the individual component materials shown in Table 6-17 and Table 6-18.

ACSS and ACSS/TW

The ACSS conductor is a thoroughly tested conductor that is commercially available from multiple vendors in the United States. ACSS was first invented in the 1960s and has been sold widely in North America for more than 30 years. It consists of fully annealed aluminum wires (1350-O) stranded over a core of high-strength, extra–high-strength (EHS), or ultra–high-strength (UHS) steel, with other characteristics being similar to ACSR conductor. ACSS demands a modest cost premium over regular ACSR when compared with other HTLS conductors. ACSS is typically available with either round aluminum strands (ACSS) or trapezoidal aluminum strands (ACSS/TW). The ACSS/TW conductors are available with aluminum area equal to ACSR of the same name or with the same overall diameter. It is possible to obtain any of these ACSS conductor designs with various combinations of corrosion coating (for example, hot-dipped galvanizing, aluminum cladding, or zinc–5% aluminum–mischmetal alloy).

Figure 6-44
Cross section of ACSS/TW conductor

ACSS (or ACSS/TW) has the thermal elongation rate of its steel core starting at a lower temperature than ACSR; the operating temperature can go as high as 300°C with Zn-5Al-mischmetal coating on the steel core wires. With ordinary hot-dipped galvanized steel core wires, ACSS is limited to 180°C continuous. Trapezoidal-shaped aluminum strands (see Figure 6-44) are often used in order to reduce electrical resistance when reconductoring existing lines. This reduces line losses and usually yields higher ratings than round-strand ACSS.

If the ACSS or ACSS/TW conductor is prestressed, the tension in the annealed aluminum strands is quite low and its self-damping is quite high. This allows its installation at smaller everyday sags than ACSR and helps to reduce or prevent vibration fatigue damage in challenging installations such as river crossings.

If ACSS or ACSS/TW is not prestressed, and the installed tension in the aluminum layers remains near the yield point of the annealed wires, wind vibration may cause aluminum strand fatigue with a greatly reduced number of vibration cycles. For this reason, if the conductors are not prestressed, manufacturers recommend the use of dampers.

Although ACSS and/or ACSS/TW can be pulled in and sagged using the same procedures used for ACSR, particular attention needs to be given while stringing ACSS conductors. As the outer layer of the conductor is made of soft annealed aluminum strands, ACSS should not be dragged across the bare ground or over rocks, fences, and the like. Parallel jaw grips should be closely sized to the conductor diameter. The clamp surface needs to be clean to minimize strand distortion.

The splicing, installation, and termination of ACSS or ACSS/TW is not more complicated than for ACSR conductors. However, the annealed strands, being very soft, should be handled with care. Furthermore, because of the annealed aluminum strands, the two-stage ACSS compression splice is somewhat longer than those designed for an ACSR conductor are. Care should be taken, because of the soft nature of the aluminum strands, to use free rolling and clean groove stringing equipment. Tension-stringing installation is straightforward. ACSS requires no special suspension clamp design; however, high-temperature–tolerant suspension clamps must be used with ACSS or ACSS/TW to allow the maximum operating temperature that these HTLS conductors are capable of reaching.

In regions of severe corrosion (for example, northern Europe) where greased ACSR is traditionally used, the use of ACSS or ACSS/TW is uncertain. ACSS or ACSS/TW is not normally available with a greased core. If it were, the cost of applying special high-temperature grease to the core would be likely to increase the cost of the conductor considerably. Furthermore, because the aluminum strand layers normally become loose over time, the conductor's ability to hold the grease in place in uncertain.

The most recent development in ACSS conductors is the ACSS-HS285. HS285 is a UHS ACSS conductor with a steel core that is up to 36% stronger than a standard ACSR core while being able to withstand up to 285 ksi (1965 MPa). HS285 can be strung tighter with less sag, allowing for a 60 to 95% increase in available capacity over standard ACSR.

G(Z)TACSR (Gap Conductor)

G(Z)TACSR, Gap-type Thermal-resistant (TAL) or super–thermal-resistant (ZTAL) zirconium aluminum alloy ACSR conductor, is commercially available in the United States, though not manufactured there. G(Z)TACSR has a unique construction. There is a small gap between the steel core and the innermost trapezoidal-shaped aluminum layer such that the core can move independently from the aluminum layer, allowing the conductor to be tensioned on the steel core only (see Figure 6-45). The original gap-type design had only the inner aluminum layer trapezoidal, with round-wire strands used for outside layers. The new design has all outer layers in a trapezoidal shape to maintain compact stranding and to minimize electrical resistance and increase the effective cross-sectional area on aluminum strands. The steel core is especially strengthened to increase the safety factor, because the core is responsible for withstanding the entire tensile load at high temperature. However, at low temperature the full hard aluminum strands carry load and help to limit sag under ice and wind loads. This effectively fixes the conductor's knee-point to the erection temperature, allowing the low-sag properties of the steel core to be exploited over a greater temperature range.

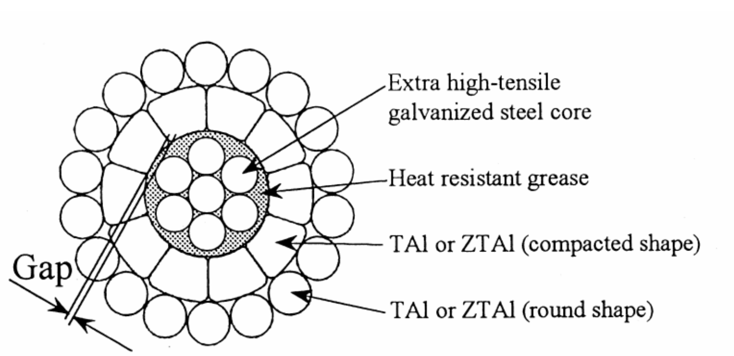


Figure 6-45
Cross section of G(Z)TACSR conductor

The gap is filled with heat-resistant grease (filler) to reduce friction between the steel core and the aluminum layer and to prevent water penetration. The aluminum layers are made up of either TAL (150°C) or ZTAL (210°C) heat-resistant zirconium alloy aluminum strands. Either type of zirconium aluminum alloy has a conductivity that is only slightly less than 1350-H19 (60% versus 61.2% IACS).

G(Z)TACSR is a Gap-type super (Z) Thermal-resistant aluminum alloy ACSR conductor built with a higher heat-resistant aluminum–zirconium (Al–Zr) aluminum alloy and EHS galvanized steel core. With a small quantity of Zr added during smelting of aluminum, there is a significant improvement in current carrying and annealing characteristics. GZTACSR can be operated continuously at 210°C without loss of tensile strength.

A special procedure is required during the installation of the G(Z)TACSR conductor. The aluminum layers of the conductor must be de-stranded, exposing the steel core, which can then be gripped by a come-along clamp. The conductor is then sagged on the steel core, and after compression of a steel clamp, the aluminum layers are re-stranded and trimmed, and the aluminum body of the dead-end clamp is compressed. Although this special erection technique is different from that employed with conductors of standard construction (ACSR), the compression splices and bolted suspension clamps are similar. In addition, to ensure proper performance of this conductor, a special type of suspension clamp hardware must be installed at every three suspension spans.

National Grid, UK has successfully installed about 300 km (185 mi) of GTACSR in its 400-kV line. More than 1500 km (930 mi) have already been installed in Libya. The Electricity Generating Authority of Thailand (EGAT) has also installed about 500 km (310 mi) of gap conductor, and it plans to add more in its 220-kV system. In addition, there are other installations (more than 300 km, or 185 mi) in Saudi Arabia, Qatar, and other Asian countries. Extensive laboratory test data and detailed installation instructions are also available from the

manufacturer. The installation of this conductor is more complex and labor intensive than ACSR. Its termination requires the unwinding of aluminum wires at each termination and splice. The high-temperature thermal elongation has been verified by test. Special semi-strain–type suspension fittings are required for the long lines.

The special construction of gap-type conductors and their increased capacity require that accessories and the possible combinations that involve the accessories be specially designed. Some examples of accessories that are peculiar to certain HTLS (for example, gap type) conductors are shown in Figure 6-46, which shows the termination procedure for a GTACSR conductor before being installed. Here, the aluminum strands are shown as the crew is separating them to grip the steel core. Because the conductor core is responsible for carrying 100% of the tensile load of the conductor, compression-type dead-end clamps used in gap-type conductor require a relatively larger size than those used for ACSR with the equivalent diameter, to allow for the increased current capacity.

Figure 6-46
Removal of gap conductor strands at the termination at the EPRI Lenox Lab

Gap conductors have grease in the gap between the core and the aluminum strands. This grease needs to be replaced with high-temperature grease before the steel end is crimped to grip the core at 50% overlap (see Figure 6-47).

Unlike ACSR conductors, gap-type conductors require that the conductors must be installed so the aluminum layers are compressed while only the steel core is under tension, to gain maximum benefit from the small-sag properties. Similarly, as the wire stranding construction of gap-type conductor is different from that of ACSR, and the current capacity is large, unique designs for termination hardware are also required for gap-type conductors.

Figure 6-47
Application of high-temperature grease on core-grip portion

(Z)TACIR (Invar)

(Z)TACIR is a Zirconium Alloy Aluminum Conductor Invar[12] steel Reinforced conductor. The conductor is similar to the ACSR conductor (see Figure 6-48); the major difference being that the core is made of high-strength Invar alloy wire instead of conventional steel wire. Invar is an alloy of steel (64%) and nickel (36%). Nickel possesses a very small linear coefficient of thermal expansion, which is practically invariable with heat. This property results in low sag at high temperature beyond the knee-point temperature; thus, it is recommended to operate beyond the knee point. This conductor has relatively low sag at higher temperature. (Z)TACIR has a maximum continuous operating temperature of 210°C and has twice the current capacity of ACSR conductor. The coefficient of linear expansion of Invar wire (2.8 to 3.6×10^{-6}) is about one-third of that of galvanized steel wire. However, tensile strength of Invar wire (1080 MPa) is lower than galvanized steel wire. Tensile strength of the conductor is about 8% lower than that of the normal ACSR conductor. Because the conductor has the same structure and size as those of ACSR, the stringing method is also identical to that of ACSR.

[12] *Invar* is a registered trademark of Imphy Alloys.

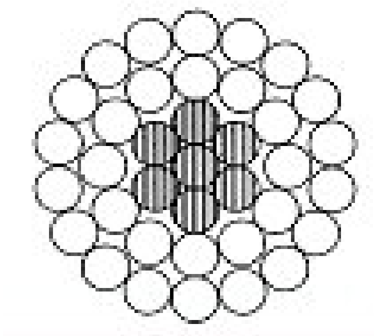


Figure 6-48
Cross section of (Z)TACIR conductor

ACCR and ACCR/TW

ACCR is built with outer layers of heat-resistant aluminum–zirconium (Al–Zr) or annealed aluminum wires (round or trapezoidal) and a proprietary fiber-reinforced aluminum matrix composite core (Figure 6-49). Both the composite core and the outer Al–Zr strands contribute to the overall conductor strength and conductivity. The outer alloy aluminum wires are either round or trapezoidal and of the same construction type as ACSR conductors. The composite core has a lower thermal elongation property and equal or greater strength than galvanized steel. The core wire looks physically similar to steel core, but it is eight times stronger than aluminum and about the same stiffness as the steel core. Each core wire contains thousands of small-diameter, UHS, and aluminum oxide fibers. The ceramic fibers are continuously oriented in the direction of the wire, and fully embedded within high-purity aluminum. Currently, 3M is the only manufacturer of this type of conductor, and the production unit is based in Wisconsin.

Figure 6-49
Cross section of ACCR conductor

The strength of this core is comparable to steel, but it possesses additional properties. For example, the alumina fibers have a lower thermal expansion than aluminum or steel; the core has a greater resistance to corrosion; it exhibits lesser creep; and it has no undesirable magnetic properties. It can operate continuously at 210°C. The outer wires surrounding the composite core are made up of high-temperature-resistant ZTAL strands. ZTAL aluminum limits the maximum operating temperature of the ACCR conductor.

In 2001, Xcel Energy successfully completed a field test of ACCR conductors in its 115-kV system in Minneapolis to replace equivalent ACSR conductors. More than ten utilities have now successfully installed ACCR conductors in their systems; these include Hawaiian Electric, Arizona Public Service (APS), Bonneville Power Administration (BPA), Western Area Power Administration (WAPA), and Pacific Gas and Electric (PG&E). Field test results appear to be positive, with no unusual problems during installation or afterward. The installation of this conductor appears to be reasonably straightforward but may require special large blocks and careful handling. 3M has conducted various mechanical and electrical tests that meet the criteria for the conductor and associated hardware mechanical and electrical integrity.

Under a Department of Energy (DOE) project, a two-span ACCR line was tested in Oak Ridge National Laboratory (ORNL) at high temperature for an extended period. ORNL published multiple field trial reports on “477,795 kcmil, 675 TW, and 1272 kcmil ACCR conductor.” 3M has invested considerable engineering effort in studying the details of the conductor’s and the accessories’ behavior under the realistic high-temperature conditions of this study. 3M has also developed technical information, including installation guidelines and laboratory test results, for ACCR conductor and accessories. 3M also provides technical support to the potential users of ACCR conductors.

The compression-type hardware for the dead-end assembly of ACCR conductors uses a modified two-part approach, as in the ACSR or ACSS conductor. One part grips the core, and then an outer sleeve grips the aluminum strands, as shown in Figure 6-50. The gripping method ensures that the core grip evenly loads the core strands and ensures that the outer aluminum strands suffer no lag in loading relative to the core.

Figure 6-50
Termination of ACCR HTLS conductors

ACCC and ACCC/TW Conductor

Aluminum Conductor Composite Core (ACCC) cable was developed to improve several key performance metrics over conventional ACSR conductors. A lightweight circular-shaped advanced composite core, designed as a single piece rod, acts as a mechanical support. High-performance, trapezoidal-shaped, fully annealed 1350-O aluminum strands fit well around the circular surface of the core in a helical shape with minimum interstices compared to the conventional ACSR conductor (see Figure 6-51). This increases the effective cross-sectional area for aluminum strands, increasing the current carrying capacity. The cross-sectional area of the aluminum Suwannee (ACCC/TW) conductor is 30% higher than the equivalent diameter ACSR (Drake).

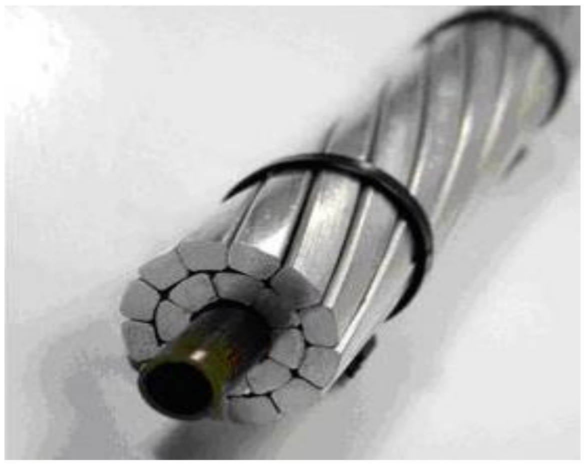


Figure 6-51
Cross section of an ACCC conductor

To increase the strength of the conductor, a carbon/glass fiber, polymer matrix composite core is used to replace the stranded steel core used in ACSR conductor. Carbon fibers are situated in the core and are surrounded by a “shell” of E-glass fibers, as shown in Figure 6-52. The composite core in the ACCC is a low-density material with much lower coefficient of thermal expansion (CTE) and a high strength-to-weight ratio. The density of the composite is 1.935 mg/m^3, whereas the density of steel is 7.78 mg/m^3. The annealed aluminum strands allow operating continuously at elevated temperatures of up to 200°C with dramatically less sag.

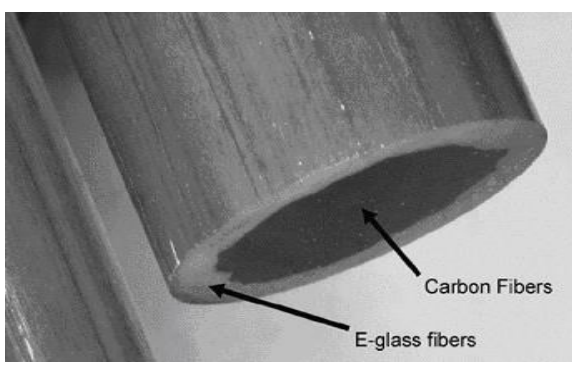


Figure 6-52
ACCC core showing the glass and carbon fiber

The composite core used in the ACCC conductor is a solid, single-piece rod with no interstices, unlike cores in ACSR and ACSS conductors. As the core has a smooth surface and it bears the overall *tensile* strength of the conductor, the dead-end assembly (Figure 6-53) has been designed to create a stronger crimp compared to that of an ACSR conductor, which forms a very solid aluminum press that fits around the composite core.

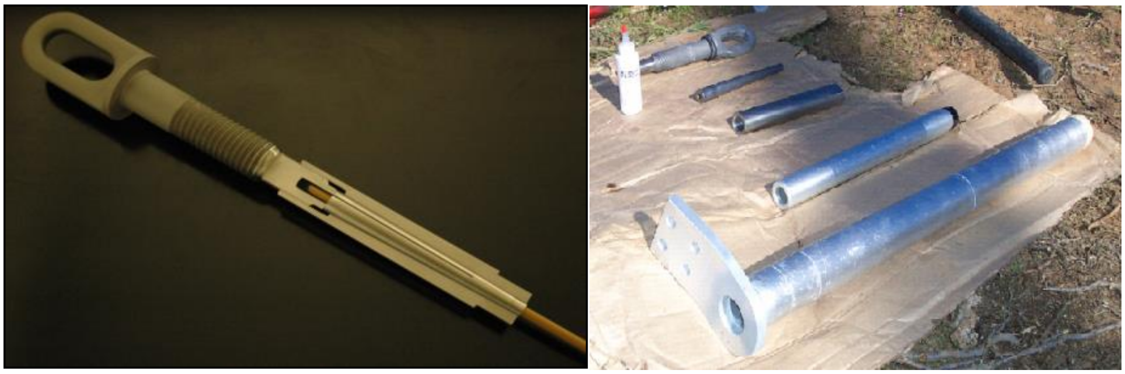


Figure 6-53
Dead-end fittings hardware used for ACCC conductor

HVCRC Conductor

Mercury Cable & Energy labeled its conductor HVCRC—High Voltage Composite Reinforced Conductor. Its composite core is almost identical to the ACCC conductor, with the exception of the difference in color of the material at the center of the core, as shown in Figure 6-54. As with the CTC conductor, the carbon fibers are embedded in resin to form the center core, which is covered by an E-glass fiber shell. The HVCRC conductor consists of a few layers of annealed aluminum wires stranded around the carbon fiber composite core. The HVCRC conductor is rated at a maximum operating temperature of 150°C.

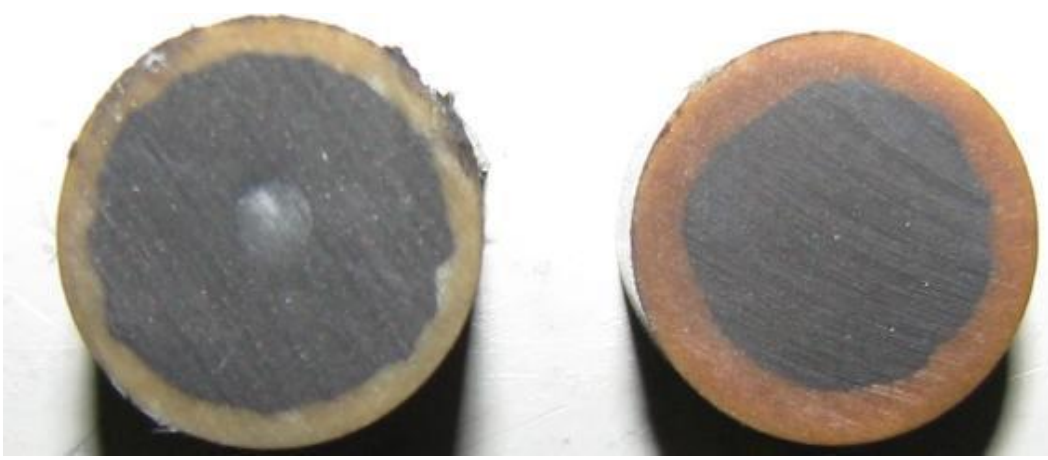


Figure 6-54
Cross-sectional views of mercury cable (left) and CTC (right) composite cores

Lo-Sag Conductor

Nexans Cable labeled its carbon fiber composite core conductor “Lo-Sag,” from the characteristic of low sag that it produces compared with traditional ACSR conductors. Similar to the other carbon fiber composite core conductors, it consists of a single composite core covered with two or more layers of annealed, trapezoidal-shaped aluminum wire strands. Unlike the ACCC and HVCRC, the carbon fiber core is protected by a plastic shell, which, in turn, is covered by an aluminum sheet on top. Figure 6-55 shows the cross-sectional view of the Nexans Lo-Sag conductor. The conductor is rated at a maximum operating temperature of 180 to 200°C.

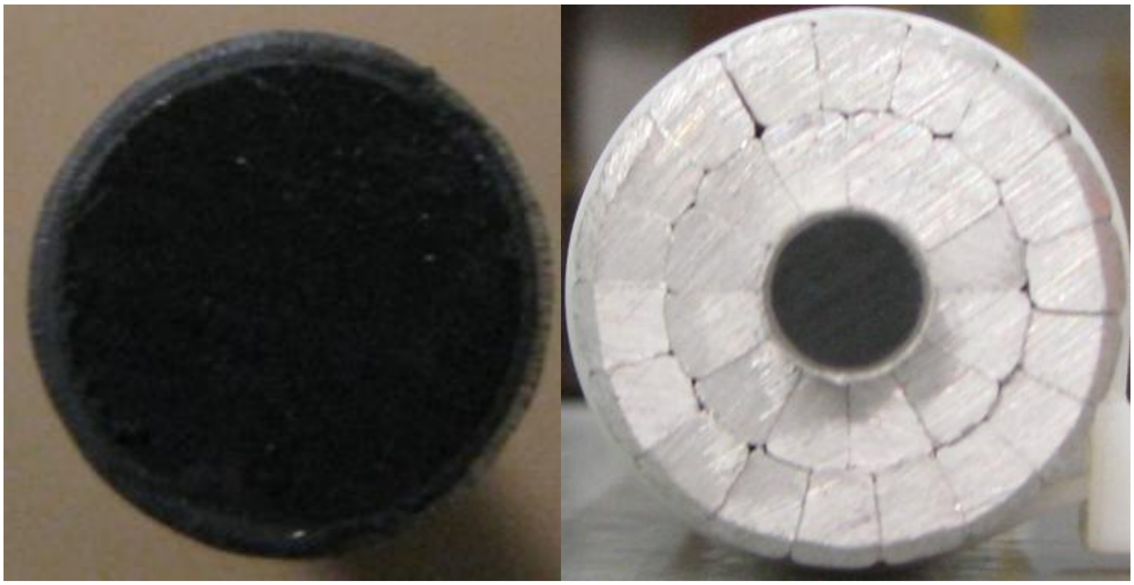


Figure 6-55
Cross-sectional views of Nexans cable—core (left), entire conductor (right)

C^7 Overhead Conductor

Southwire and Celanese have collaborated on a new composite core conductor utilizing Celstran® CFR-TPR as the core strand marketed as C^7 Overhead Conductor. The core consists of a multi-stranded composite core of Celstran® continuous fiber-reinforced thermoplastic rods (CFR-TPR) which provides greater flexibility of the core and avoids single-point failure mechanism, see Figure 6-56. The conductor can be stranded with trapezoidal strands of Aluminum Zirconium (AlZr) or 1350 0-temper Aluminum strands. Maximum operating temperature is 225°C.

Figure 6-56
Southwire C^7 multi-strand composite core conductor

C7 can be applied on new line designs where long spans are required with minimal sags or for upgrades where C7 conductors can provide twice the capacity of the existing ACSR conductors.

Details of the long term aging tests conducted by EPRI can be found in, Accelerated Aging Tests On High Temperature (HTLS) Low Sag Conductor Systems, PID: 3002007503 and Advanced Conductor Long-Term Accelerated Aging Performance Evaluation, PID: 3002019289.

Cost Comparison of HTLS Conductors

HTLS conductors are more expensive than conventional conductors from the initial investment perspective are. However, HTLS conductors can carry significantly higher current compared with the conventional conductors for the same equivalent aluminum area. The cost associated with conventional conductors can be comparable—or sometimes higher, when we take into account the upgrade cost for transmission towers and accessories, including land and environment, for the equivalent current that HTLS conductors can carry. Table 6-20 shows the cost of various HTLS conductors with similar cross-sectional area. The cost includes the cost of the conductor only. Other technical characteristics of the conductor, such as the sag and tension behavior that determine whether structure modifications are required, must be considered to determine the overall cost of replacement. The conductor length for the U.S. system covers ACSR conductors above 230 kV.

Table 6-20
Price, ampacity, and installed inventory of HTLS conductors, as of 2015

Conductor	Current Capacity	Price	Conductor Length (miles)
Conventional ACSR (Aluminum Conductor Steel Reinforced)	1	1	> 500,000 in U.S. (230 kV and above)
ACSS (Aluminum Conductor Self Supported) Round Trap	1.6x 1.6x + cost of Add'l Al	1.2x (HS steel core) 1.5x (HS285 UHS core)	> 34,000 in US > 800 with HS285
C^7 (ZTACCR and ACCS) (Aluminum Conductor Composite Reinforced and Aluminum Conductor Composite Supported)	1.5x	5x	Not Available at the time
GTACSR (Gap)	1.6-2.0x	2x	17,000
*ACIR (Invar Core)	1.5-2.0x	5x	12,000 (4,000 (Z)TACIR)
ACCR (Aluminum Conductor Composite Reinforced)	2x	5–6.5x	1,267
ACCC (Aluminum Conductor Composite Core)	2x	2.5–3.0x	19,564
HVCRC (High Voltage Composite Reinforced Core)	Not Available at the time	Not Available at the time	Not Available at the time
ACPR (Aluminum Conductor Polymer Reinforced) Lo-Sag	≥2x	4-6x	2,738

* Data correct as of 2015 **Note**: 1 mi = 1.6 km

The price figures are obtained from the respective manufacturers. This economic comparison does not consider the economic benefits associated with greater revenue generated as a result of increased current throughput capacity from HTLS conductors.

The following list shows some good opportunities for HTLS conductor based on certain constraints:

Table 6-21
HTLS application guide

Conditions	Potential HTLS Solutions
Polluted Areas – concerns for steel core corrosion	Composite core conductors Aluminum coated core strand GAP conductor
High Ambient Temperatures – want High Temperature Conductor (HTC) with higher operating limits	HTC with annealed aluminum
Ice Prone Areas – want high strength cores to sustain mechanical loads	Extra High Strength ACSS, Carbon Core with Aluminum Zirconium outer strands
Limited Sag at High Ampacity	Carbon fiber cores Invar Steel core
Long Spans – high strength with low sag	Carbon fiber core
Rebuild Existing Lines – need minimum sag for same tensions to mitigate structure change outs	Low sag composite conductors that provide less sag at same tension with increased power flow

More information on HTLS conductors can be found in, Guide for Selection and Application of High-Temperature Conductors: 2019 Update. EPRI, Palo Alto, CA: 2019. 3002015651.

HTLS Field Testing

A co-operative project was undertaken in 2004, aimed at evaluating the new emerging HTLS conductors. It was a joint effort between the funding utilities and manufacturers. The project aimed to demonstrate and raise the confidence for using HTLS conductors and thus accelerate the application of the technology to increase power flow in the existing transmission circuits.

The project and this report, position utilities as "informed buyers and users" of this technology and avoids duplication of research and test work completed by others in the industry.

This section provides an overview of the EPRI HTLS project, with a description of the scope, conductor types, tasks, funding members, and participants.

Scope

This project answers the following key questions:

Conductor Performance

- **Field Trials.** What characteristics of operating experience with the conductors can be gained from the field trials?

- **Manufacturer Claims.** How do published manufacturer claims compare to field and laboratory performance?

Design and Engineering

- **Design Parameters.** What are the design parameters (as required by line designers) for these conductors?
- **Engineering Changes.** What engineering changes (compared to standard ACSR) are necessary when designing, specifying, ordering, shipping, handling, installing, inspecting, and maintaining these conductors?
- **Existing Tower Design.** What is the impact of these new conductor types on the existing tower design? Do towers need to be redesigned to accommodate these conductors? What tower features inhibit the use of these conductors?
- **Handling**. What special handling precautions apply when shipping conductors and when handling them on site?
- **Installation.** What special tools and precautions are needed when installing these new conductors? What factors need to be considered when installing these conductors (e.g., slack-stringing versus tension-stringing)?

Conductor Aging

- **Aging Factors.** How do these conductors age, and what factors influence aging? Further, how does aging affect performance? How does the long-term, mechanical performance of these conductors compare to the traditional conductor ACSR?
- **Long-Term Performance.** What is the long-term performance of line hardware, especially splices and dead-ends? Performance covers repeatability of installing reliable splices and dead-ends and also equipment needed to install a splice.
- **High-Temperature.** What is the effect of sustained high-temperature operation on the conductor, splice, and dead-end?
- **Connection.** How should these high-temperature conductors be connected to existing line conductors?

Conductor Fittings

- **Long-Term Performance.** How do these devices perform under high temperature over long periods of time?
- **Laboratory Performance.** Under accelerated environmental conditions, how do these products perform, and are there any concerns about the long-term integrity of these products?
- **Specifications.** What factors should be considered when specifying a conductor fitting for a particular operating environment?

Economics

- **Refurbishment Costs.** What is the cost comparison for upgrading existing lines with the various HTLS conductors?

- **New Line Costs.** What are the comparative "costs of operation" and "lifetime costs" when installing and operating networks using these new conductors as compared with conventional ACSRs?

Inspection and Condition Assessment

- **Inspection.** What techniques should be used to inspect and assess the condition of the conductors?

Application Engineering Guidelines and Training

- **Guidelines.** What application guidelines and training materials are useful? What form should these materials take, and how should they be delivered?

Issues Not Addressed

This project did not address the following issues:

- **Grid.** This project does not explore the impact of these new conductors on the grid system. Upgrading the transfer capacity of a particular line within a grid system will alter power flow patterns. Changes in these patterns may potentially lead to network instability. This project focuses purely on line upgrades and performance.
- **Sag Properties:** HTLS conductors generally operate with stable mechanical properties at high temperature and elongate less with temperature than conventional ACSR or AAC conductors. However, the development of conductor sag-tension and stress-strain parameters is not within the scope of this project.
- **Speculative Designs.** Conductors at the research and development stage are not covered. This project evaluates only commercially or near commercially available conductors. The products considered are limited to manufacturers that are capable of manufacturing conductor in the quantities required in typical refurbishment projects.
- **Acceptance Tests.** This project does not aim to repeat standard conductor acceptance tests. Therefore, the project only considers conductors that have already passed most or all accepted industry standard tests.
- **New Conductors.** This project does not intend to develop new conductors.

Conductor Types

To address the issues within the project scope, conductors proposed initially for investigation were:

- ACSS or ACSS/TW (Aluminum Conductor Steel Supported, where the designation TW indicates that the aluminum wires are Trapezoidal Wires rather than round)
- GTACSR (Gap–Type, Thermal Resistant Aluminum Conductor, Steel Reinforced)
- ACCR (Aluminum Conductor Composite Reinforced)
- ACCC (Aluminum Conductor, Composite Core)
- CRAC (Composite Reinforced Aluminum Conductor)

  CRAC was a conductor proposed by Goldsworthy, as a result of a research project funded by the California Energy Commission. However, the manufacturer never manufactured the conductor or offered it for sale. Instead, ACIR (High Temperature Aluminum Conductor Invar-steel Reinforced) was selected. In ACIR, an Invar steel core (a steel alloy with high nickel content) replaces the galvanized high strength steel core and high-temperature Zirconium aluminum replaces the 1350-H19 aluminum strands of a conventional ACSR.

The HTLS conductors for the project were supplied by:

- Southwire of Carrolton, Georgia, for the Aluminum Conductor Steel Supported Trapezoidal Wire (ACSS/TW)
- 3M of Minneapolis, for the Aluminum Conductor Composite Reinforced (ACCR)
- CTC of California, for the Aluminum Conductor Composite Core (ACCC)
- J-Power System, Japan, for the Gap-Type Aluminum Conductor Steel Reinforced (GTACSR)
- LS Cable, Korea (formerly LG Cable) for the Zirconium-Type Aluminum Conductor Invar steel Reinforced ACIR)

Tasks

The scope of work included six tasks, described as follows:

Task 1 – Test Site Selection

Candidate test lines and associated test spans were evaluated. Suitable sites for the high-temperature, low-sag conductors were then selected. Four sites were chosen for the five conductors, as shown in Table 6-22. Line designs were performed for the conductors. This exercise also generated the engineering tasks for reconductoring.

Table 6-22
Conductor test sites

Host Utility	Field Trial Location	Data Collected Since…..Ending in May 2008	Conductor Tested
CenterPoint Energy	Houston, Texas	May 26, 2003	ACSS/TW (Southwire)
Hydro One	Ottawa, Canada	October 24, 2004	GZTACSR (J Power) ZTACIR/AW (LS Cable)
Arizona Public Service	Phoenix, Arizona	June 17, 2005	ACCC (CTC)
San Diego Gas & Electric	Oceanside, California	July 21, 2005	ACCR (3M)

Task 2 – Reconductoring

This task included the purchase of the conductor, temporary removal of the existing conductor, possible modification of the towers, installation of the new conductors and associated line hardware, and commissioning and energizing the line.

Task 3 – Field Monitoring, Laboratory Testing, and Interim Reporting

This task covered the selection and installation of field-monitoring equipment, such as video Sagometer, load cells, vibration recorder, and weather stations to monitor the long-term performance of the conductors and associated hardware. Conductor sag and tension were monitored continuously through video Sagometers and load-cells. During each site visit, measurements were taken of electric and magnetic field profiles under the transmission lines, hot spots on surfaces of conductors and hardware (such as splices, dead-ends, and towers), splice resistance, and vibrations. These field measurements provided utilities with necessary information on the operational performance of new HTLS conductors through approximately three years of field trial experience.

Task 4 – Development of Supporting Engineering Guidelines

Under this task, EPRI developed and delivered engineering guidelines covering the design, specification, installation, inspection, and maintenance of these HTLS conductors. These guidelines are to be in the form of a demonstration on installation, videos of the field installation, a workshop, and a final technical report. These guidelines are appropriate for line designers, line inspectors, and field and maintenance crews.

Task 5 – Final Reporting

This final technical report is to document and analyze instrument field data, manufacturer recommendations, and utility experiences in a final project report. The report is also to include recommendations, engineering application guidelines, and an analysis of costs.

Task 6 – Test Site Decommissioning

This task assumes that the host utility wishes to remove the conductor from the test spans and restore the line to its original conductor. Removal of HTLS conductors is under host utility's discretion.

Schedule

Field trials of these HTLS conductors were started in the summer of 2003. Originally, it was planned that each type of conductors would be subjected to three years of high operating temperatures. Due to difficulties in procuring HTLS conductors and in acquiring field trial sites, the project was extended by one year to enable the project to collect three summers of high operating temperature data.

Funding Members

Twenty utilities funded this project. Among them, 15 utilities are from the United States, two from Canada, and one each from United Kingdom, Spain, and France.

1. American Electric Power (AEP)
2. American Transmission Company (ATC)
3. Arizona Public Service (APS)
4. California Energy Commission (CEC)
5. San Diego Gas & Electric (SG&E)
6. Southern California Edison (SCE)
7. Pacific Gas & Electric (PG&E)
8. CenterPoint Energy
9. Duke Energy

10. Exelon
11. Hawaii Electric
12. Long Island Power Authority (LIPA)
13. Southern Company
14. Tennessee Valley Authority (TVA)
15. Xcel Energy
16. British Columbia Transmission Company (BCTC), Canada
17. Électricité de France (EDF), France
18. Hydro One Networks, Canada
19. National Grid, UK
20. RED Electrica de Espana (REE), Spain.

The results of this demonstration project can be found in: High Temperature Low Sag Conductor Field Trial: Summary of Results. EPRI, Palo Alto, CA: 2018. 3002012674.

HTLS Experience

Since the completion of the original EPRI HTLS demonstration project in 2009, a number of HTLS conductors have been installed in the United States and overseas. Some of the HTLS conductors installed around the world can be found in the appendices. This section will ultimately include a number of case studies, providing the readers a source of reference and insights into the rationale that justified the selection of a particular HTLS conductor. The basis for the selection of a HTLS conductor could vary, from technical, economical, time restraint or other merits. Table 6-23 gives an overview of the case studies which EPRI has documented.

Table 6-23
Overview of conductor case studies

No.	Utility	Conductor Used	Voltage	Reason for Using HTLS Conductors
1	BPA	ACCR (3M)	500 kV	Able to replace a single conductor with a bundled system without modifying towers.
2	AES Eletropaulo	ACPR Lo-Sag (Nexans)	138 kV	New circuit with mechanical and Right-of-Way restrictions due to urban region.
3	Elia	ACPR Lo-Sag (Nexans)	380 kV	Uprate the single conductor double circuit with a twin bundle configuration. One circuit adopted used the Lo-Sag conductor.
4	Southern Company	ACCR (3M)	115 kV 230 kV	Able to uprate the single circuit while maintaining mechanical loadings and clearances. Able to uprate one circuit of the double circuit towers while maintaining the mechanical loading.
5	Northern Ireland Electricity	ZTACIR G(Z)TACSR	Double circuit 110 kV Single circuit 110 kV	Uprate, a double circuit using Invar conductors, as well as a single circuit H wood frame with Gap conductors, without any structural modification.

Table 6-23 (continued)
Overview of conductor case studies

No.	Utility	Conductor Used	Voltage	Reason for Using HTLS Conductors
6	Western Area Power Administration (WAPA)	ACCR (3M)	230 kV strain bus bar	Uprate the substation strain bus bar meeting the original sag requirements.
7	AECC	ACCR (3M)	161 kV	Uprate the line meeting the clearance requirements on a river crossing using the existing structures.
8	Entergy	ACCR	230 kV	Uprate the line using the existing steel poles maintaining the sag profile.
9	Lower Colorado River Authority (LCRA)	ACCR/TW (3M)	138 kV	Uprate the line on fours spans of a lake crossing, meeting required clearance for sailing, considering extra ice loading on conductors.
10	CenterPoint Energy	ACSS/TW	345 kV	New line replacing existing twin bundle conductor on lattice towers line with a single conductor.
11	American Electric Power (AEP)	ACCC/TW	138 kV 161 kV 345 kV	Uprate existing lines on constrained Right-of-Way, minimizing structure modifications and keeping the required clearance.
12	Tenaga National Berhad (Malaysia)	ACCC	275 kV	New line allowing increased capacity and lower line losses over baseline design.
13	City Power Johannesburg	HVCRC (Mercury Cable & Energy)	88 kV	Doubling the capacity of the network under peak loading conditions, keeping the existing towers without clearance encroachment.
14	Avista	ACSS E3X (General Cable)	115 kV	Uprate existing line on constrained Right-of-Way while minimizing structural changes, increasing capacity due to high emissivity of conductor surface.
15	Cheyenne Light, Fuel and Power Company	ACCC E3X (E3X General Cable)	115 kV	Uprate one circuit of a double circuit line due to a large and unexpected load increase, keeping original structures and mechanical load limits. The E3X coating was added to the design to maximize ampacity.
16	TIWAG-Netz AG	ZTACIR	220 kV	Increase the line capacity required for meeting N-1 constraints during outages.
17	Arizona Public Service	ACCS-C7 (Southwire)	69 kV	Increase the number of 69 kV underbuilt circuits in a 230kV double circuit structure to meet the load growth.
18	Nevada Power	ACCC	220 kV	Uprate the line capacity requirement from 300 A to 1000 A keeping the existing structures and the desired clearances.
19	Cross Timbers	ACSS ACCR	345 kV	ACSS was used for lower sag at maximum operating temperature. Use of ACCR to avoid “in-river” structures on a river crossing with flat terrain.

Compact Tower Designs

Technology Overview

A compact transmission line may, be defined as a line where the lateral dimensions of the line - tower height, tower width, and minimum right-of-way (ROW) width - are reduced relative to older existing lines of the same voltage class.[1]

Initial attempts to achieve compact line configurations stemmed from the need to achieve increased transfer capacity on existing Right of Way corridors in urban areas. However, a number of different forms of line compaction are evident in the industry, described as follows:

Types of Compact Tower Designs

Horizontal Compaction

Horizontal compaction seeks to compact phases with the minimum lateral extension. This is typically achieved by the use of vertical phase arrangements (see Figure 6-57).

Horizontal compaction, which emanates predominantly from ROW restrictions, may refer not only to the compaction of phase arrangements, but also the limitation of supporting structure footprint. This is especially relevant where shared use of the ROW is present, or where limited space is available due to the presence of unavoidable obstacles or structures close to the tower site (see Figure 6-58).

The use of monopoles have the most relevance to such cases, while structures that are less likely to be useful include multiple (H) poles, lattice and guyed configurations (in that order).

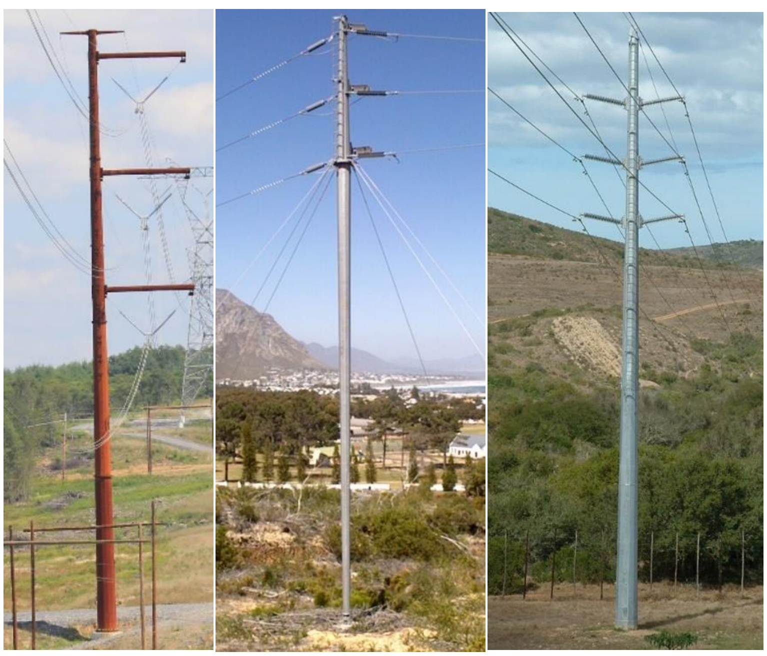


Figure 6-57
Horizontal compaction of circuits

Figure 6-58
Footprint limitations are most prevalent in shared use ROW's

Horizontal compaction of phases has also been used to achieve electrical benefits. For example, the two 765kV guyed structures illustrated in Figure 6-59 represent first and second generation supports. In the second generation, horizontal compaction of circuits was pursued in order to improve electrical efficiency and to reduce electric fields at ground level (see). This form of compaction was considered beneficial in spite of some structural inefficiencies introduced by the compaction arrangement.

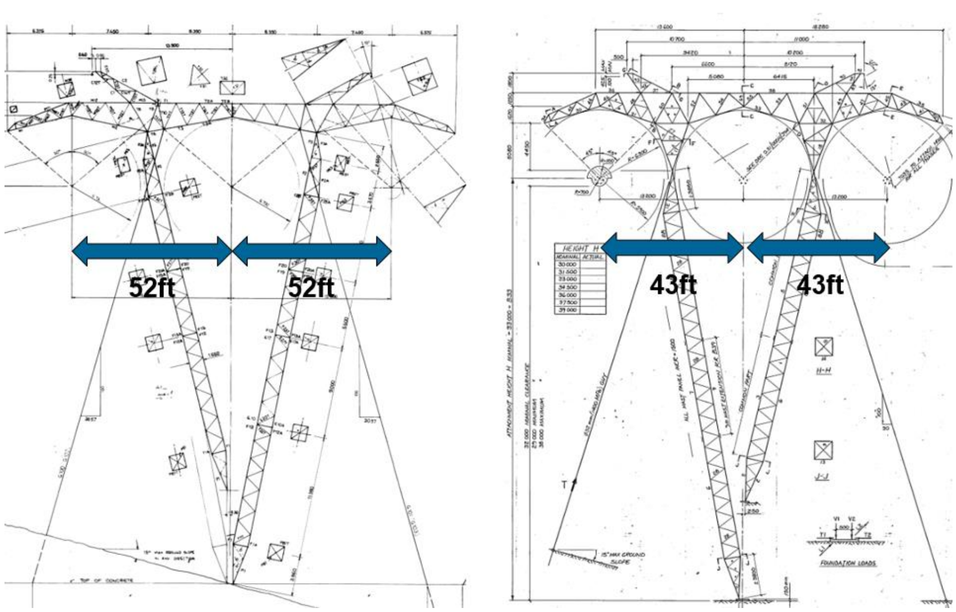


Figure 6-59
Horizontal compaction of 765kV phases for the purposes of electrical efficiency

Vertical Compaction

Conversely, vertical compaction of single circuits mostly implies the use of horizontal phase configurations.

Vertical compaction of a may be possible (and preferable) in locations where sufficient lateral space is present in the ROW, but visual impact needs to be minimized. Such structures may include locations where total structure height is minimized to enable reduced visual impact as illustrated in Figure 6-60.

Figure 6-60
Vertical compaction of double circuit line to facilitate screening by vegetation

An interesting vertically compact configuration is the "compactLine" design illustrated in Figure 6-61. What is unique in this application is the use of highly tensioned phase conductors to achieve half the sag in comparison to conventional applications, thus further reducing the structure height and visual impact. These high tensions were achieved by using the steel cable outside of the aluminum conductors, which may be suspended below the steel support wires. This type of connection allows of highly effective damping, since the suspended arrangement behaves similar to a "Bretelle" damping system.

Figure 6-61
Vertical compaction of double circuit line [Courtesy of 50hertz Transmission/ SPIE SAG]

In other vertically compacted applications, both delta and vertical circuits may be temporarily rotated through a flat configuration as an effective means of constructing underpasses under a crossing line as illustrated in Figure 6-62.

Figure 6-62
Vertical compaction of double circuit to facilitate underpass

The use of vertical compaction for the purposes of structural efficiency (reduced overturning moment) is illustrated in Figure 6-63, where a vertically compacted tower top geometry is achieved on a double circuit strain pole by using horizontally supported jumpers. In this example, the increased insulation cost is more than offset by the reduction in both structure and foundation costs.

Figure 6-63
Vertical compaction of double circuit strain pole to reduce tower top size

Phase Compaction

Phase compaction of phases refers to the convergence of the three phases in a circuit, most typically in a delta orientation, and / or a combination of vertical and horizontal phase compaction, for the purposes producing electrical efficiency. Phases arranged in triangulated arrangements may be referred to as having a delta (△), inverted delta (▽) or rotated delta (▷) orientation.

Compaction for electrical efficiency is most effectively achieved where circuits are brought as close as possible to each other in an equidistant delta configuration, within a tower window, as illustrated in Figure 6-64. Partial electrical compaction may be achieved where circuits are arranged in a flatter delta formation as illustrated in Figure 6-65.

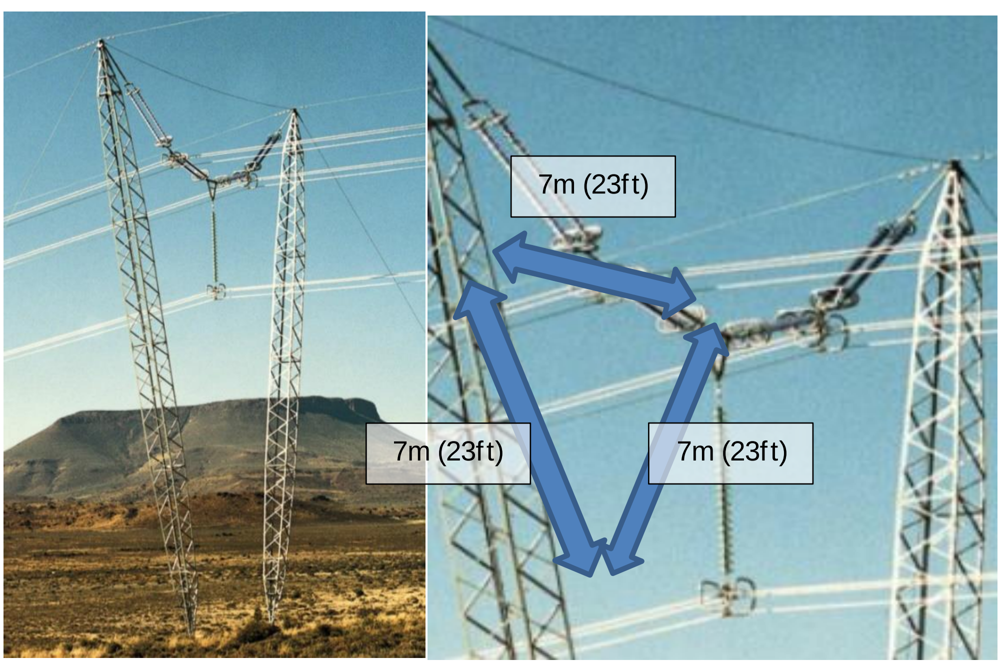


Figure 6-64
Phase compaction on a 400kV crossrope structure

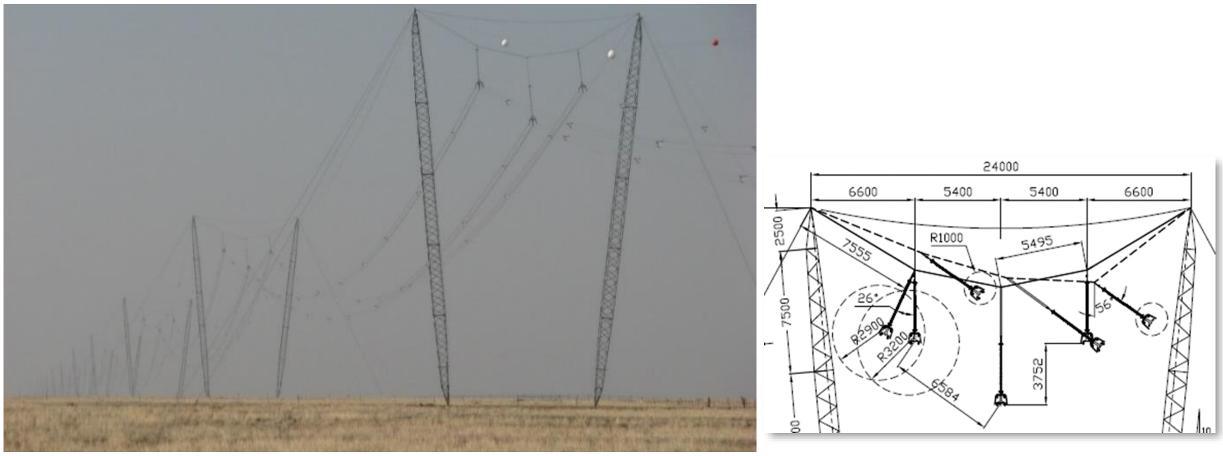


Figure 6-65
Flat-delta" phase compaction on a 400kV cross rope structure

Where circuits are arranged in a delta formation on either side either side of a pole or main body, the electrical benefits of compaction are to some extent negated, and in such cases, the primary benefit is a combination of both vertical and horizontal phase compaction. The use of single circuit delta formations is a common format utilized in single circuit pole and lattice structures, as illustrated in Figure 6-58 and Figure 6-66.

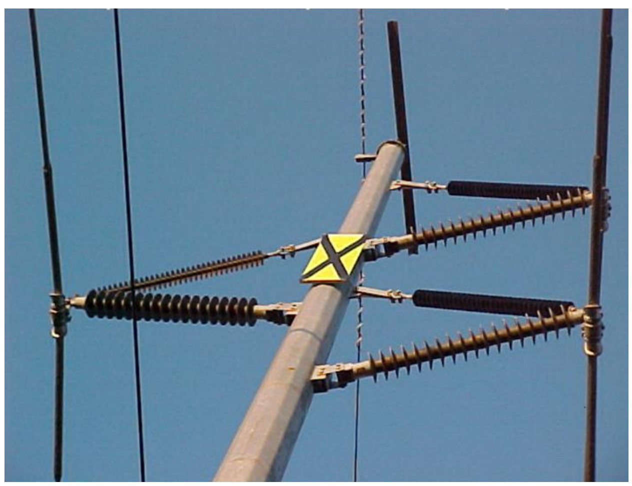


Figure 6-66
Delta phase compaction on a 132kV monopole

Phase Compaction Due to Voltage Upgrading

As highlighted in the EPRI Blue Book [1] and Cigré Brochure 792 [17], lines which have been subjected to voltage upgrades, by definition become compact lines. Multiple examples of such designs exist (see Figure 6-67 and Figure 6-68) and have been successfully operated.

Figure 6-67
230-kV structure prior to conversion to 345 kV [1]

Readiness of Technology

In summary, the state of readiness of compact line design may be regarded as mature technology, due the large number of successful designs in service. However, there are both advantages as well as challenges relating to the adoption of compact designs, and designers should be made well aware of both the potential gains as well as the pitfalls associated with the technology - but more importantly – how to deal with negative aspects relating to compact designs.

EPRI Transmission Line Reference Book: 115-345 kV Compact Line Design (Blue Book) [1], enumerates benefits associated with compact design, including allowance for narrower rights-of-way, reduced magnetic & electric fields, and to minimize the visual impact of transmission lines. This type construction can also be the answer to increasing capacity on an existing rights of way.

Line compaction brings a number of benefits are summarized in Table 6-24. A number of challenges have also been identified, which should not necessarily be viewed as disadvantages, but as rather aspects requiring specific attention during the design stage. The number of successful, operational compact designs bear testament to validity of compact designs as a support option, and in these applications designers have paid specific attention to address the challenges.

Table 6-24
Benefits and challenges of line compaction

Benefits	Challenges
Ability to upgrade lower voltage lines	Implementing aesthetically designed lines Increased Corona
Magnetic and electric field decreases	Increased corona
Increased power transfer	Insulation co-ordination
Reduced Visual impact	Maintenance on compact lines
Compacted servitudes	Design for iced conditions
Reduction in Installed Cost	

Benefits of Line Compaction

Ability to Upgrade Lower Voltage Lines

While the focus of this report is on the design of new compact lines, it is worth noting that many initial examples of power line compaction were borne from the need to increase power transfer by upgrading voltages and re-using the same support structures.

The finite amount of space within a support structure originally designed for operation at a lower voltage becomes significantly constricted as the operating voltage increases, and some novel approaches, together with careful engineering and testing have resulted in significant increases in the operational voltage. For example, an early test line was operated successfully at 138 kV with a horizontal phase spacing as low as 3 ft.[1]

In another example (see Figure 6-68), the operational voltage of a 66kV line was increased to 110kV by the addition of 4 additional insulator discs, coupled with horizontal stabilization of phases using post insulators. In this case, the horizontal stabilization also included the permanent support of I-strings at a 45^{o} angle to the vertical, thus reducing the impact of the increased vertical clearance requirement above ground level.

The recycling of existing supports also has particular significance in instances where public opposition to new projects is present, since increases in visual impact are low.

Figure 6-68
66 to 110 kV line upgrade

Numerous examples of voltage upgrades are covered in the EPRI Red Book [1], Chapter 14.

Magnetic and Electric Field Decreases

Concerns relating to the potential effects of electric and magnetic field remain a significant public concern. In some EHV applications, typically above 500kV, electric fields may dominate the design, and can result in greater mid-span clearance requirements than those required by electrical flashover considerations.

Commonly accepted limits as promoted by independent organizations like ICNIRP, (International Commission on Non-Ionizing Radiation Protection), promote the limitation of electric fields at the ROW boundary to below 5kV/m, and magnetic fields to a limit of 200 μT. Other standards have adopted limits lower than these.

While reduced phase spacing increases electric fields at the conductor surface, at ground level, both the electric field and magnetic field is reduced.

Figure 6-69 shows the results of a recent Cigré Study [4] which evaluated the field effects across the ROW width at ground level. From this comparison the reduced field effects afforded by phase compaction is clear. Peak electric fields were reduced in the order of 30%, and Magnetic fields were reduced in the order of 20%.

These results are particularly significant when considering the possibility of building higher voltage lines on a constricted ROW previously used for a lower transmission voltage.

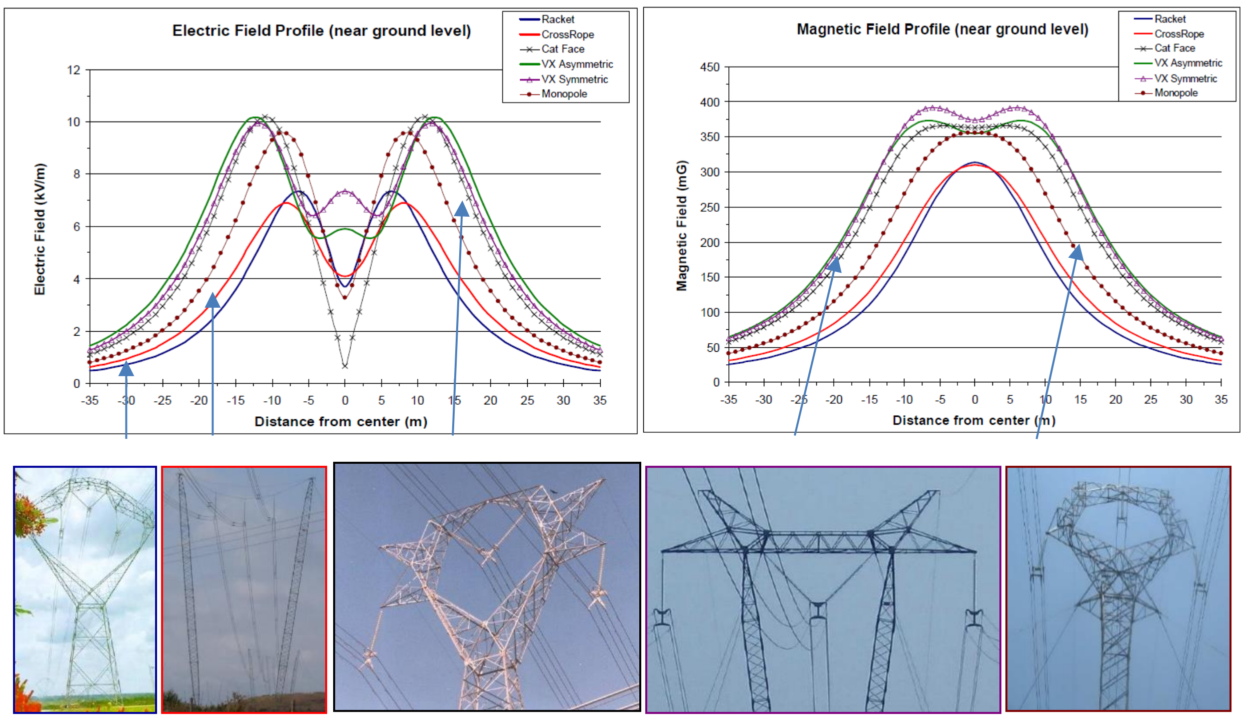
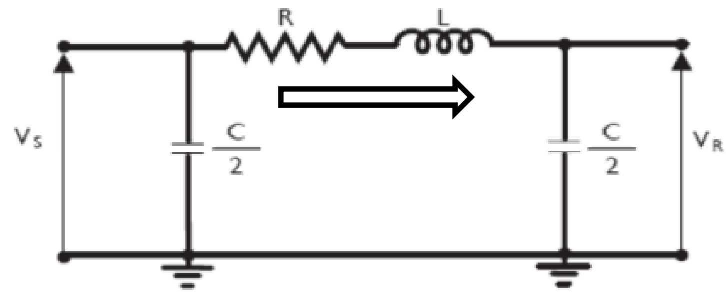


Figure 6-69 Electric magnetic field near ground level for various 500kV configurations [4]

Increased Power Transfer

The electrical characteristics affecting power transfer are conceptualized in Figure 6-70, which shows a simplified electrical diagram of an overhead line.



V_S – Sending Voltage
V_R – Received Voltage
R - Resistance
L - Series Inductance
C - Shunt Capacitance

Figure 6-70
Simplified electrical representation of an overhead line [7]

Where the power transfer capacity of a line is regulated by resistive (thermal) limits, transfer capacity is a function of ampacity, which is not affected by phase compaction.

Longer lines, (typically in excess of 150 mi.), or any lines where power transfer is limited by voltage constraints (typically due to the type of dominant industrial load), can also benefit from phase compaction. Compaction of phases, both increases the shunt capacitance (C) and also decreases the series inductance (L) of the line, thus reducing the positive sequence surge impedance (Z_S) of the line, according to the following relationship:

$$ZS = \sqrt{L/C},$$

with L being the series inductance and C the shunt capacitance of the line.

Reducing the impedance of the line results in a reduced voltage drop on the line and a higher surge impedance line loading ability. The Surge Impedance Loading (SIL = VLL2 / ZS) of a transmission line is the value of active power that, flowing through it, provides equilibrium between the reactive power generated in the line's shunt capacitance (C) and the reactive power consumed in the series reactance (XL). The SIL, also called the “Natural Power” or “Natural Capacity", and transmitting at this power value, there is almost no voltage drop.4 Lines that employ phase compaction have a high surge impedance loading (HSIL) ability.

The maximum benefit from line compaction is obtained when the phases are arranged as close as possible to each other within the same tower window, as illustrated in Figure 6-64, whereas configurations employing phases that are compact, but separated by structural components, have some, albeit reduced, HSIL ability. Further significant increases in SIL are possible by employing expanded bundles, as used frequently by Brazilian transmission utilities (see Figure 6-69).

It is important to note that HSIL becomes useful specifically where the line is appropriately loaded, and lightly loaded HSIL lines could be affected negatively by overvoltage at the receiving end, potentially requiring the addition of reactors to consume reactive power. Conversely, lines with low SIL may require the addition of more capacitor banks to support the voltage, which implies that an optimal SIL may exist for each line.

Visual Impact

Public opposition and growing environmental awareness make planning future power lines for transmission challenging, and opposition groups are becoming increasingly well organized and well informed. With increased public resistance to the construction of new overhead lines, utilities must seek ways of reducing the visual impact of lines.

New overhead line developments are often constrained to the re-use of existing utility corridors, but such developments are often coupled with transmission at higher voltage, resulting from increased loads. Where recycling (voltage upgrading) of existing structures is not practical, new, higher voltage lines have to be constructed on the same right of way. In such cases, the potential visual impact is especially significant where the proposed construction of new, higher power lines are visible from a greater distance over the landscape (see Figure 6-71).

In these cases, vertically compacted phase configurations will preferred from a visual impact point of view.

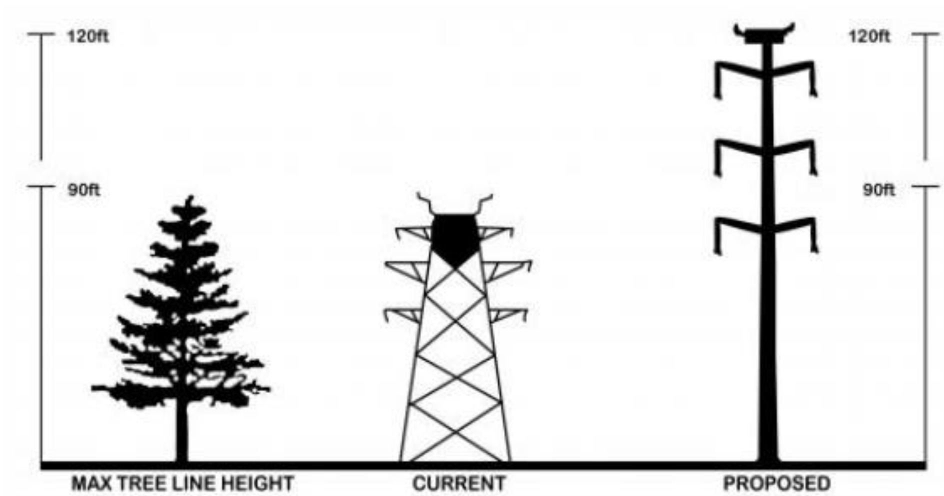


Figure 6-71
Illustrated visual impact from introduction of higher voltage line [5]

Aesthetically designed structures can represent an effective method of achieving public acceptance of overhead line projects, and the use of compacted phase arrangements are also commonly deployed on such concepts, as illustrated in Figure 6-72, Figure 6-73 and Figure 6-74.

Figure 6-72
Compacted phase arrangement on aesthetically designed structures [6]

Figure 6-73
BOLD tower
(Courtesy of BOLD Transmission, LLC)

Figure 6-74
T-Pylon tower

(Courtesy of National Grid)

Compacted Servitudes

The use of horizontal compaction to accommodate overhead lines on constricted servitudes is becoming more prevalent, especially in urban and semi - urban centers experiencing power demand growth.

NESC C2-2012 requires that horizontal clearances also consider the movement of insulators, conductors and pole deflection (after conductor blowout under an operational wind pressure of 290Pa / 6psf). Hence, the use of V-string suspension assemblies or post insulators assist in limiting the resultant right of way (ROW) restrictions (see Figure 6-75).

As illustrated in this figure, the resultant ROW restrictions are likely to be well in excess of the footprint of the structure.

Additional ROW width restrictions may prevail when considering NERC requirements for vegetation clearance, which requires a minimum vegetation clearance (MVCD) to be maintained between blown-out wires and vegetation. NERC standard FAC 003, which covers Transmission vegetation management, does not specify the wind pressure to be used when determining the horizontal position of blown out conductor, but implies that all operational conditions should be considered.

Finally, utilities should also consider vegetation maintenance intervals and potential growth to prevent trees from falling or growing into live conductors.

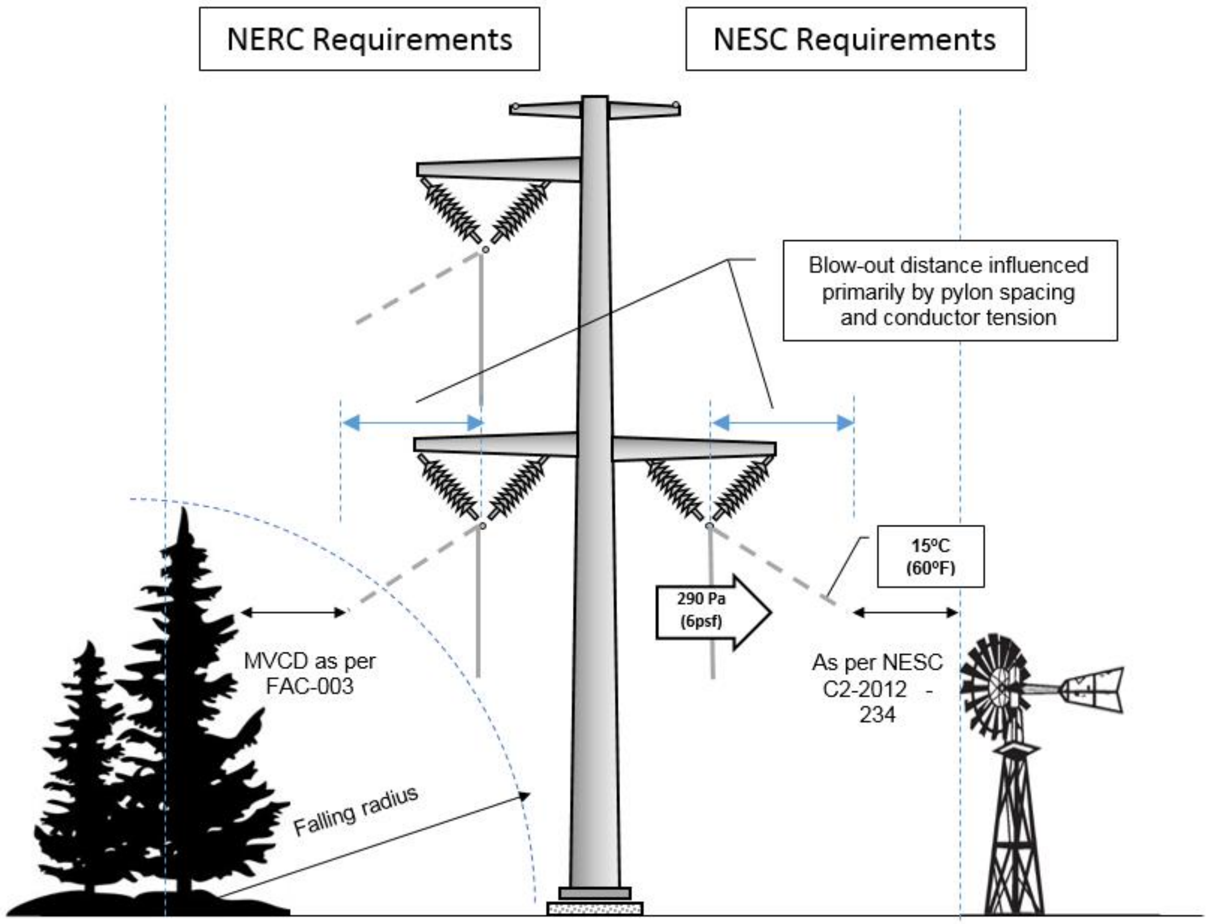


Figure 6-75
Determination of ROW and clearance to other structures

Further reductions in the blow-out are possible by controlling the maximum span length. Where such maximum span limitations are present on significant portions of the line length, it becomes beneficial to ensure that both the attachment height requirements and design span limits are reduced in harmony with the ROW restriction.

Reduced Cost

Depending on the type of compaction, some modest cost reductions may be possible due to compacted designs, which further discussed below under the section: Vendor landscape and approximate costs.

Challenges Associated with Compact Lines

When compact lines are considered, designers must be mindful of the key design parameters that are negatively affected by compaction and ensure that the resulting design has duly considered and amounted for these impacts.

The intention of this section is to highlight such design issues and to indicate ways in which the impact has been mitigated.

Implementing Aesthetic Designs

The emergence of some ambitious designs as seen in recent pylon design competitions often include compact phase configurations and, while inspirational from an architectural perspective they can be challenging when considering engineering and cost implications, potentially being multiples more expensive than conventional line designs.

The challenge to utilities is to extract practical design concepts from these concepts or possibly to consider the application of "sculpture towers", where one or two such structures are placed in high visibility locations.

Increased Corona

Electric field increases at the conductor surface as phases are brought together, thus potentially increasing corona activity. Increased corona produces line losses, electromagnetic interference, audible noise and accelerated aging on insulation.

The EPRI Blue Book[1] and provides specific guidance on corona with respect to compact line design, while the EPRI Red Book[2] dedicates three chapters to corona.

Insulation Co-Ordination

The selection of appropriate insulation to protect a compact design against temporary over-voltages under polluted conditions, as well as under switching and lightning conditions is a significant design consideration, as it is with any standard structure configuration. These design aspects are covered in the EPRI Blue Book[1] in chapters 4-6.

It is worth noting that while compromises in insulation strength may or may not be present in certain line upgrades (where the space available in an existing tower top geometry is limited by the existing configuration), the majority of new compact lines will seek to obtain the same level of electrical performance enjoyed by a standard, non-compacted design.

Certain insulator configurations, such as post and braced post solutions, lend themselves to compact configurations by virtue of their compact design, elimination of cross-arms, and reduction in conductor swing under wind.

Since electric fields may be higher in compact designs, the use of corona rings may be required to limit the electrical field gradient to lower than 0.35kV/m in the vicinity insulator end seals.[1]

Switching surges, which normally are significant where line voltages exceed 345kV, may need to be considered at lower voltages compaction of phases has been employed. In cases where switching surges could dominate the design, switching over-voltages may be reduced through the use of pre-insertion resistors, surge arrestors, or synchronized closing of circuit breaker poles.[1]

Certain aspects of compacted designs have a beneficial impact on lightning performance. Lower, more compact arrangements may attract fewer lighting strokes, however where compaction is significant, or where shield wires have been eliminated to produce extremely compact designs, the use of surge arrestors may be required. (Concepts where shield wires have been eliminated in EHV lines as in Figure 6-76 are rare and usually limited to areas with low isokeraunic levels, typically in high latitudes.)

Figure 6-76
Highly compacted 300kV design with no shield wire (Statnett) [12]

Flashovers due to lightning may increase in locations with high earth resistance (e.g. rocky or dry sandy conditions). In such locations, lightning performance may be effectively evaluated with line lightning performance prediction software such as EPRI TFlash [1], which may suggest improved earthing systems or transmission line surge arrestors (TLSA's).

Maintenance on Compact Lines

The ability to perform maintenance, and specifically live line maintenance, is a key design parameter on compacted phase arrangements. Live line maintenance involves maintaining safe utility worker working clearances during maintenance activities. MAD (minimum approach distance) working clearances are reviewed and discussed in the EPRI Blue Book[1].

The extent and practicality of compaction will also depend on the type of live line maintenance. While some utilities utilize bare hand techniques (in which linemen worker are placed in direct contact with the energized zone), other techniques use insulating tool work (where work is performed at a distance using insulating tools while observing MAD clearances).

The EPRI Live Working Reference Book (The Tan Book) [14] covers live working expensively, and Chapter 17 of the Tan Book specifically covers live working on compact lines.

Whether or not live line maintenance is an operational requirement, is probably the single most important factor which will determine the extent to which phases can be compacted. Some utilities (such as Eskom) have specified live insulator replacement as a mandatory operational requirement, whereas other implementations of compacted phase arrangements (such as National Grid's T-Pylon) have enabled reductions in phase to phase distances by excluding live maintenance.

Maintenance work on compacted or upgraded structures can take place at either under phase to earth conditions, or between phases, under phase to phase voltage.

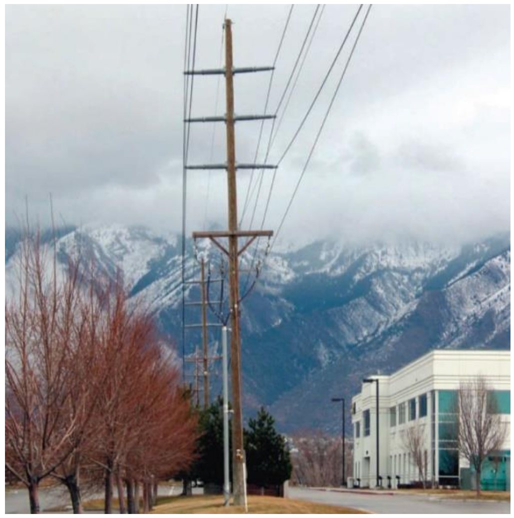


Figure 6-77
Double-circuit 138-kV compact line with 1.8m (6ft) vertical phase spacing[1]

Since phase to earth clearances in conventional, non-compacted designs are governed by minimum approach distances and dry-arc clearances on insulation, it is unlikely that phase to earth distances would be significantly different in new compact line designs. However, compromised phase to earth conditions are likely in instances where voltage has been upgraded on an existing structure, where a finite amount of space is available. Where maintenance has to be conducted under these conditions, the risk of line workers being exposed to temporary over-voltages while performing live work can be mitigated by the use of portable protective air gaps (PPAG's), or portable and/or fixed surge arrestors.

It is likely that compacted arrangements will affect the type of live phase to phase work. Vertically compacted phases on double circuit towers may prevent external access via non-insulted aerial platforms. Access to such arrangements such as the compact lines in Figure 6-63 and Figure 6-77, would need to be made via an insulated aerial platform.

Live work between compacted phase arrangements will need to consider the available space for live working tools (which may be suited for longer coupling distances) and the likelihood of increased capacitive and inductive coupling between phases of the compact arrangement.

Galloping and Ice Jumping

Galloping and Ice jumping impact significantly on the required vertical separation of phases, and design methods often suggest an increase in spacing when compared with traditional tower top geometry. These phenomena thus have a very significant impact on compact lines – specifically those requiring reduced vertical separation, and such lines will need specific consideration to mitigate and reduce movement where the incidence of ice induced motion is probable.

Galloping is a low frequency, high oscillation conductor movement of conductors caused predominantly by wind action on asymmetrical ice accretion on wires. The phenomenon is covered extensively in the EPRI Orange Book - Wind Induced Conductor Motion[9], as well Cigré Brochure 322 [10]. Mitigation with specific respect to compact lines is discussed in Chapter 3 of the EPRI Blue Book[1].

Galloping causes fatigue and failure of hardware and insulators as well as phase to phase flashovers. This latter phenomenon has particular relevance to compact designs. Frequencies can range from 0.1 to 1 Hz and amplitudes from ± 0.1 to ± 1 times the sag of the span (with higher ratios possible on short spans) [10].

Although some instances of predominantly horizontal conductor motion have been recorded[9], the most frequently observed motion path is a vertical or almost vertically oriented ellipse. Consequently, the traditional technique used to evaluate conductor motions in galloping involves tracing vertically oriented ellipses to see if there are possible points of intersection between phases. The extent of these ellipses are also dependent on whether single, double or triple loop movements are considered, with single loop galloping being the most onerous in terms of required vertical phase to phase clearances. PLS-Cadd can model single and double loop ellipses as determined according to REA Bulletin 1724E-200 and Cigré Brochure 322 methods (see Figure 6-78).

Ice jumping occurs when accumulated ice drops off a laden span, resulting in an upward acceleration of the span which, in the theoretical extreme case, can reach as high as the sag of the iced conductor, potentially flashing over to the phase above.

Consequently, both galloping and ice jumping have a greater potential to affect vertically compacted circuits than horizontally compacted or delta circuits. For this reason, vertical circuits in double circuit towers are often designed with the center (middle) phase at a lateral offset to the upper and lower phases. The use of delta circuit configurations to accommodate galloping ellipses should also significantly assist in avoiding of phase to phase flashovers from galloping or ice-jumping.

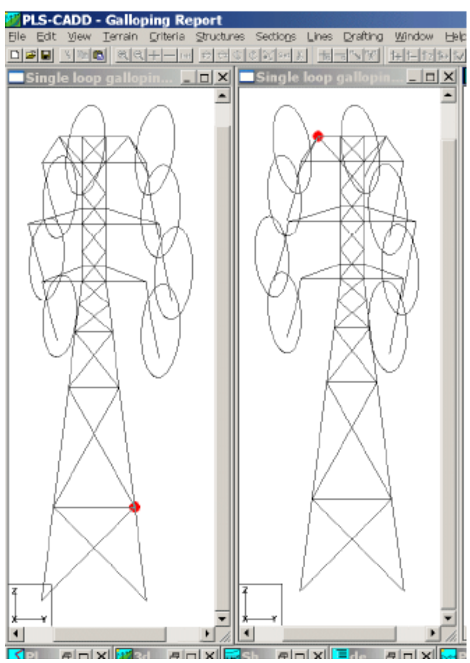


Figure 6-78
Single loop galloping ellipses as determined in PLS Cadd[11]

A number of counter measures have been successfully deployed[9] to mitigate against iced conductor motion, including:

- Thermal de-icing (Ice Melting), by increased power flow (shorting and re-routing current)
- Ice-phobic Coatings, including both covered conductors and applied coatings
- De – icing rings that promote ice falling from the conductor
- De-tuning pendulums, which disrupt the natural frequency of the span
- Ice counterweights applied at varying fractions of the span length
- Ice removing rollers that are pulled along the conductors or incorporated into remotely operated de-icing robots
- Systems that impact a lateral shockwave to the iced conductor, in which ice is shed from the conductor in the travelling wave
- Cable twisting devices to remove ice by torsional stress
- Twisted-pair conductors, which exhibit high self-damping under both aeolian and iced oscillations
- Spiral Air Flow Spoilers (which duplicate the same effect of twisted pair conductors)
- Flexible and rigid interphase spacers applied typically at $^1/_3$ or ¼ of the span length

Of the above methods, twisted pair conductors, interphase spacers, airflow spoilers, detuning pendulums and thermal de-icing methods seem to be the most widely adopted de-icing countermeasures.

Finally, the use of post insulators should be made with due consideration to vertical loads imposed by icing, which may imply the use of a braced post configuration.

Field or Testing Results

Electrical Testing

In all applications where corona is a key design challenge, HV testing is highly recommended to ensure that the design operates within parameters. Testing should cover not only the completed support assembly, but also the conductor bundle, with all associated hardware, corona rings, and insulator grading rings in place (see Figure 6-79).

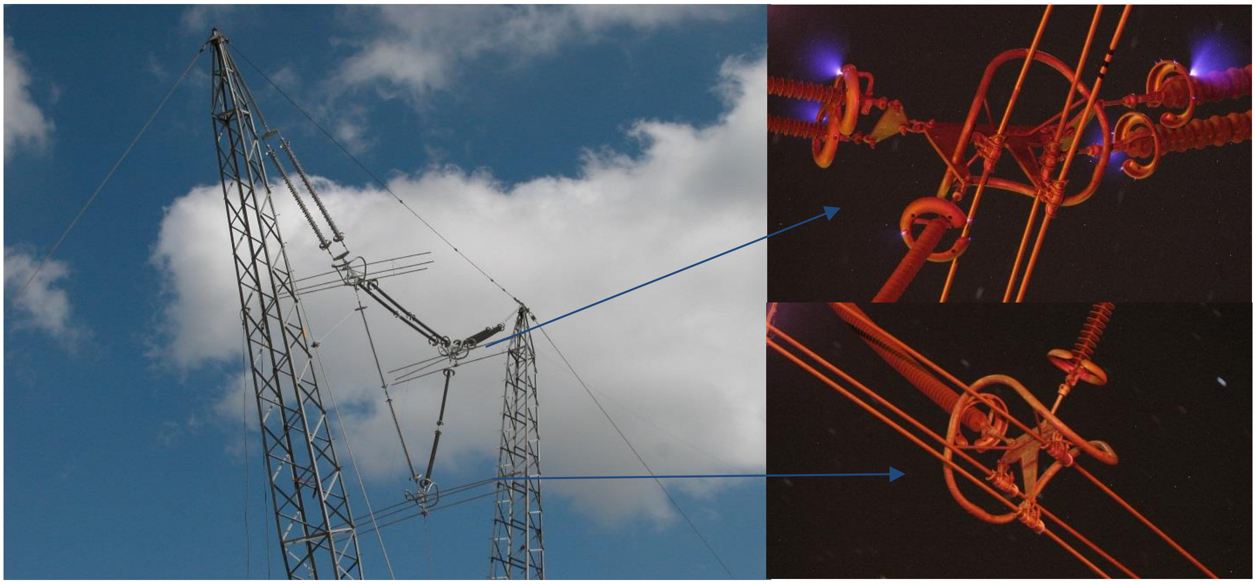


Figure 6-79
Electrical test arrangement for compact 400kV assembly [8, 13]

Corona testing on the phase conductor bundle is a separate, but equally important design check. Since corona activity decreases significantly with conductor age, testing of both aged and new conductors is recommended. If required, aged conductor can be simulated by sand-blasting the conductor surface.

Work between special arrangements, such as illustrated in Figure 6-80, will benefit from tests to confirm the safety of live workers under temporary overvoltage conditions. In the test illustrated below, the impact on a line worker, located on the star point coupling (a floating metal component between live phases) is of interest.

Figure 6-80
Electrical test of simulated maintenance on a compact 400kV inter-phase assembly [8]

Figure 6-81
Electrical test of simulated Live Maintenance of 400kV crossrope tower [15]

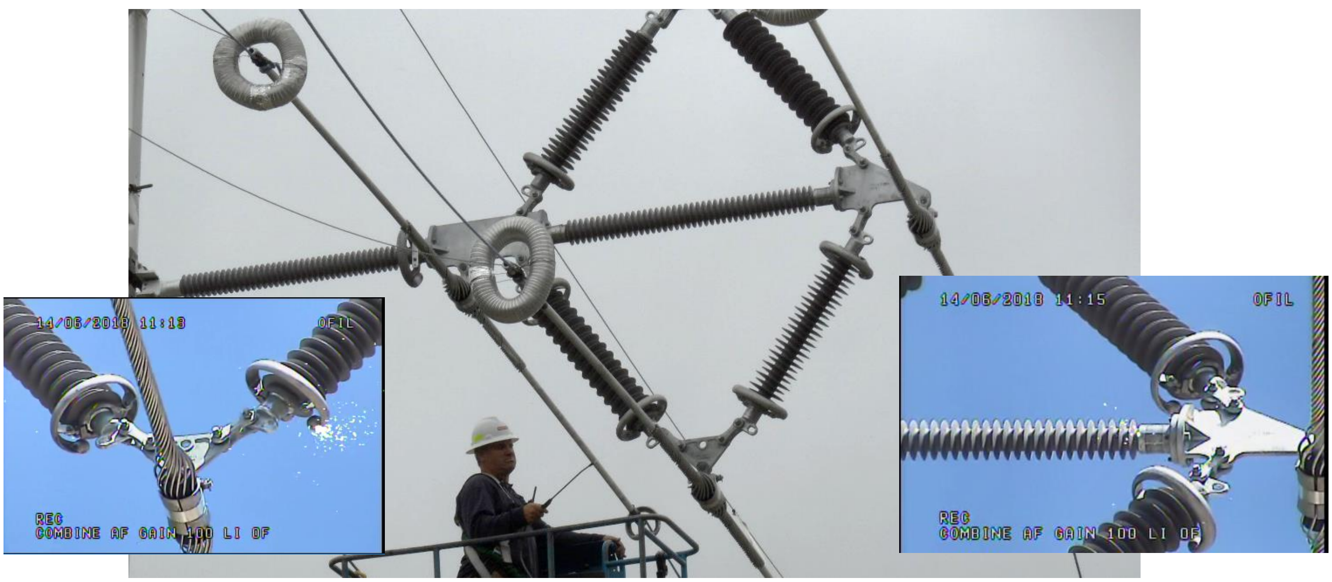


Figure 6-82
Electrical Test of simulated compact 115kV Phase arrangement [19]

Mechanical Testing

The mechanical testing of compact designs may stem from the use of unusual insulation arrangements. A good example of this relates to the testing of a compact arrangement where aa three phases were supported on the same insulation arrangement as shown in Figure 6-83.[19]

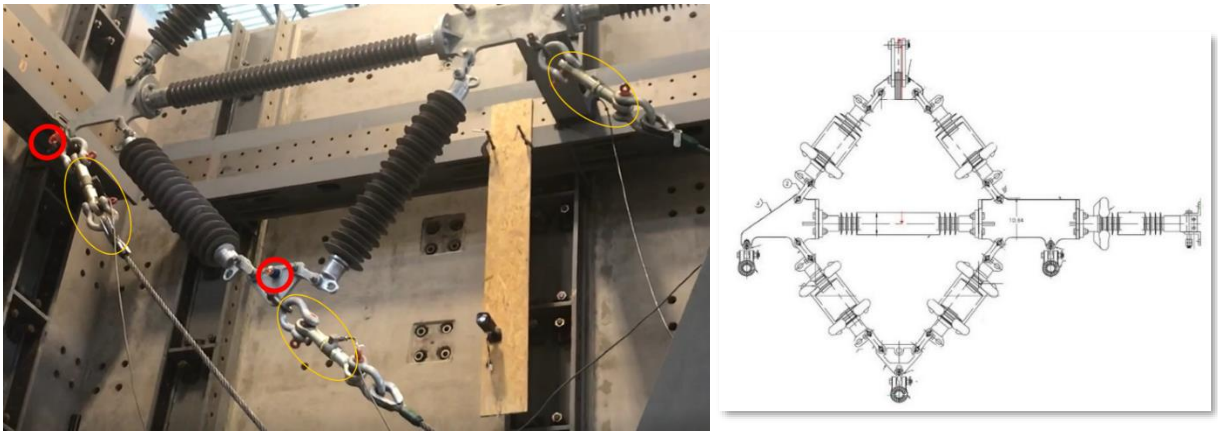


Figure 6-83
Test #1 testing assembly with laser targets (red circles) and load cells (yellow circles) indicated

In this arrangement, the testing program enabled multiple design improvements to be made, which were necessitated by different failure modes in the connection arrangement

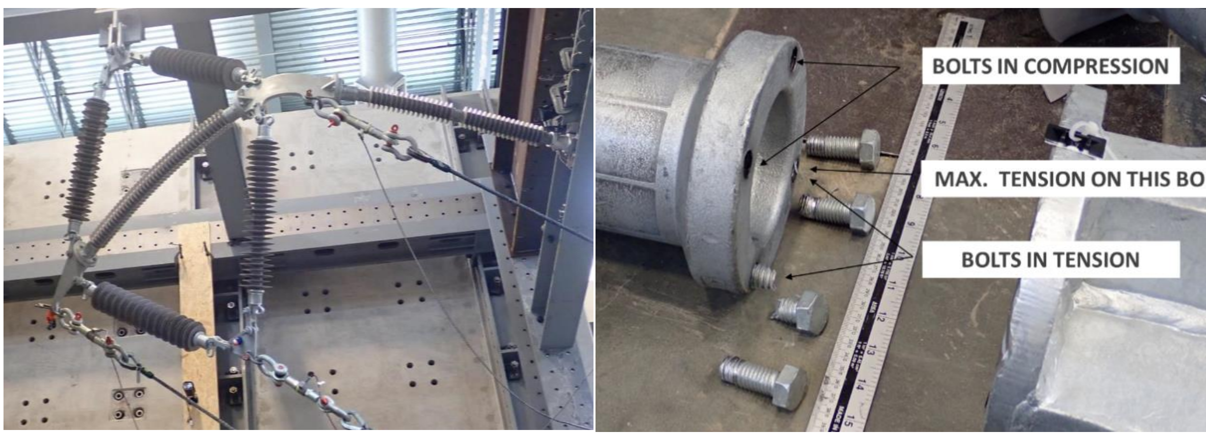


Figure 6-84
Observed buckling of post insulators and central plate, bolt failure modes[19]

In addition, such dedicated engineering studies may allow the use of higher strength factors than allowed by standard design codes. According to NESC C2-2017, the strength factor for composite post insulators is typically 0.5 (50%), unless a particular design can be proven to withstand greater loads in testing. Test #2 and Test #3 established that audible damage to the composite material in the diamond insulator assembly occurred in the region of 65%. Therefore, the NESC strength factor of the design was validated as 0.65 (65%).

Ultimately, the results of this study demonstrated the value of testing engineered designs. Throughout this test sequence, the modes of failure and weak points in the diamond insulator assembly design were identified. This resulted in numerous improvements made to improve reliability, safety, and capacity of the design. The test sequence also determined the assembly's damage limitations and actual ultimate strength.

Monitoring

The monitoring of compact phase arrangements has particular reference to features typically associated with compact phases, such as galloping oscillations, and associated mechanical stresses.

EPRI has developed a suite of sensors that may be useful to assist with in-field monitoring of conductors, insulators and structural components.

As highlighted in the previous section, galloping and ice jumping has particular significance to vertically compact phase arrangements. The use of monitors to evaluate potentially risky spans may (see

Figure 6-85) be preferable to installing anti-galloping devices, since monitoring will enable motion to be detected.

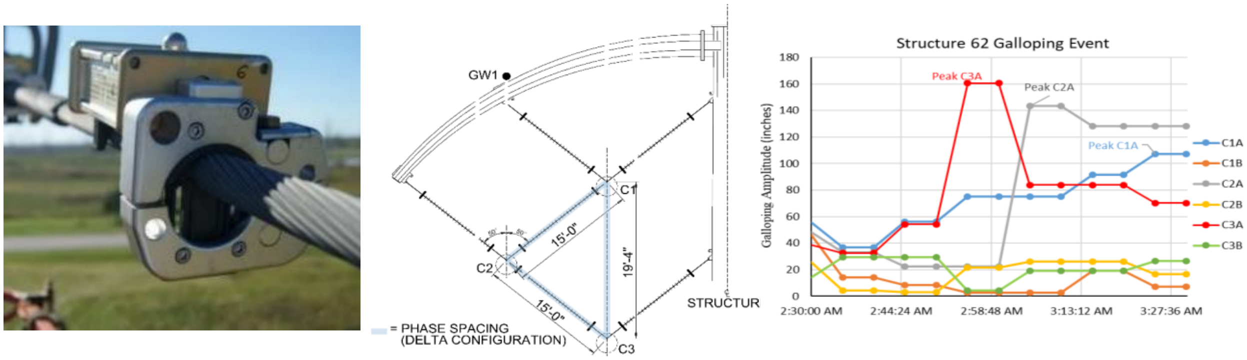


Figure 6-85
Test #1 testing assembly with laser targets (red circles) and load cells (yellow circles) indicated

In instances where components may be subjected to additional stresses, such as longer davit arms, it may be useful to monitor both movement and stress on critical components, as illustrated in Figure 6-86.

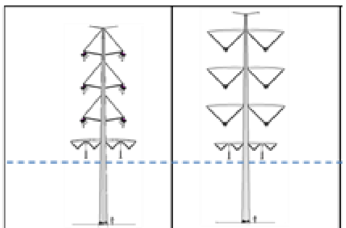
Figure 6-86
Monitoring of davit arm vibrations and strain at critical

Vendor Landscape and Approximate Costs

Cost Advantages of Compaction

A number of studies have shown that vertically compacted structures can be installed more cost effectively than conventional structures. The cost reduction is achieved primarily in the cost of the superstructure and foundations, while there may be a negative impact on the cost of insulation and hardware.

In one study[3] involving a multi-circuit 500kV + 132kV design, vertical compaction of 500kV circuits was evaluated using a horizontal vee configuration on the 500kV circuits. The increased cost of horizontal vee hardware and insulation was almost triple that of conventional v-string insulation. In spite of this, an overall decrease of 13% in the cost of the structure was achieved.



	Concept 1		Concept 2	
Hardware and Insualtion Cost	$	29 575	$	11 575
T2 Foundation Cost	$	55 032	$	59 833
Structure Cost	$	117 590	$	160 768
	$	**202 197**	**$**	**232 1**
	87%		100%	

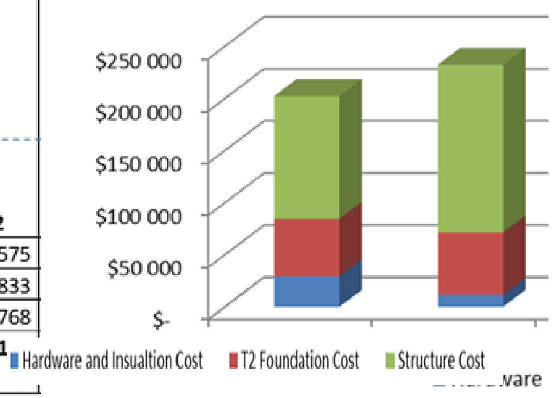


Figure 6-87
Comparison of cost on conventional vs. compacted multi-circuit concepts[3]

For lines incorporating effective phase compaction, the reduced voltage drop can also result in elimination or reduction in the capacitor banks.

Where the phase configuration is equidistant, as in many examples incorporating phase compaction, the need for transposition towers (in which phases are transposed at roughly one third and two thirds of the line length) on longer lines also falls away, producing an additional minor cost benefit.

Cost Premium Associated with Compaction and Aesthetic Designs

When compared to the most cost-effective support options possible, there is a substation cost premium associated with compact structures. This is due to the fact that substantial cost increases are associated when moving from guyed structures to self-supporting structures, especially at the higher transmission voltage levels. A parametric study was performed for various support options at 400kV, illustrated in Figure 6-88, which included the cost of all associated hardware, insulation and foundations. It may be seen that for EHV applications lattice support options are generally more cost effective than steel poles, with a 5-25 % premium associated with steel poles.

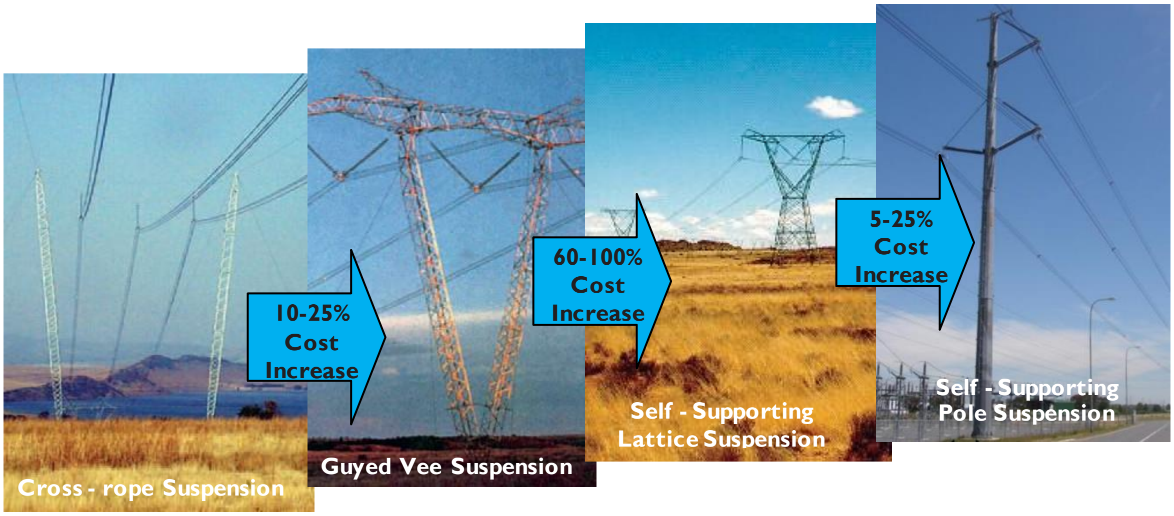


Figure 6-88
Relative cost of EHV support options (400kV)

These examples all have reference to conventional designs. When comparing the cost of these solutions with aesthetic designs, the cost premium varies widely.

Simple modifications, such as the use of curved gull-wing arms (have a low impact (1-2% of structure cost), more significant aesthetic features can have a dramatic effect on the cost.

Figure 6-89
Aesthetically pleasing lines on gull-wing cross-arms

Other compacted configurations, such as those illustrated in Figure 6-72, Figure 6-73 and Figure 6-74 which often incorporate complex fabrication and purpose designed insulation arrangements, are substantially more expensive.

When evaluating the cost of competing support options, it is important to include the relevant costs. While aesthetic transmission lines are generally substantially more expensive than conventional support options, they may still be more cost effective than undergrounding.

SF_6 Monitoring and SF_6 Alternatives

Electric utilities are facing increasing regulatory pressure and technical challenges related to the management of sulfur hexafluoride (SF_6), which is widely used as an arc-quenching medium and as electrical insulation in gas-insulated substations (GIS) and gas-insulated lines (GIL). SF_6 is a powerful greenhouse gas and at times can produce toxic decomposition products under certain fault conditions.

Several countries outside of the United States and some U.S. states have implemented or are considering regulations to limit SF_6 emissions above certain thresholds. In addition, alternatives to SF_6 have emerged. The twin challenges of increasing regulatory scrutiny and the existence of potential SF_6 replacements put the industry on the brink of significant technological disruption in this area.

The issues associated with SF_6 management and emerging SF_6 alternatives are of concern especially for utilities seeking to build new substations and lines to alleviate transmission bottlenecks, reduce congestion and allow delivery of power from renewable sources from remote or distant locations. Gas-insulated substations and lines offer many benefits including compact size, modularity, physical security and protection from pollution and harsh environments. Their compactness and modularity make them especially suitable when new substations are needed in areas where land space is limited and/or expensive, or in communities that desire visually unobtrusive power infrastructure.

The industry thus has two high-priority needs regarding GIS/GIL and SF_6: effective monitoring and diagnostic technologies to support SF_6 management, and answers to significant questions about the dielectric performance, safe and effective handling, operation, maintenance, and disposal of SF_6 alternatives. Also needed is a clear understanding of the tradeoffs and expectations utilities may experience when using the new technologies.

Technology Overview

Technology Overview: SF_6 Monitoring

Several monitoring and diagnostic technologies are available to support SF_6 management. These include:

Ultra High Frequency (UHF) Analysis – Applied to Detect Partial Discharges in GIS

The UHF technique is applied to detect partial discharges in GIS, which set up multiple resonances in the GIS chamber. These resonances are produced by the extremely fast rise-times of the partial discharge pulses. These frequencies are predominantly in the range of 400MHz-1.5GHz. These UHF signals are contained within the GIS enclosure but may be detected by external sensors at dielectric apertures on the GIS (e.g. view ports or exposed barrier boards) or by internal sensors purpose-fitted to the GIS.

For new GIS stations, internal sensors are often specified at the time of purchase. For GIS in service without internal sensors, the most common approach is to use external sensors - although some utilities have retrofitted existing GIS with sensors.

Acoustic Emission (AE) Monitoring – Applied to Detect Partial Discharges or Sparking or Moving Particles in GIS

The AE technique is applied to detect partial discharges or sparking or moving particles in GIS. Each of these three defects generates minute acoustic signals that can sometimes be detected on the outside wall of the GIS enclosure. These signals have frequency content well above the audible range. The AE detection techniques can thus filter out the background audible noise—and allow potential extraction of these low levels of high frequency signals.

Chemical Analysis – Applied to Detect By-Products from Arcing, Sparking, Corona and Overheating that Decompose SF_6

The general principle of chemical analysis is that arcing, sparking, corona and overheating decompose SF_6 into a variety of by-products. Detection of these by-products through sampling and analysis of SF_6 can thus provide clues as to whether these situations are occurring internally.

X-Ray Inspection – Applied to Provide Information about the Condition of Key Components without Dismantling

The general principle of X-ray imaging is that high frequency radiation can penetrate solid materials to various degrees, depending on the properties of the materials being penetrated with X-rays, or with electromagnetic radiation of other wavelengths.

Photographic film or other materials are used to detect and record radiation that has passed through materials subjected to imaging. Imaging materials, such as film or phosphorous plates, are also usually sensitive to electromagnetic radiation of other frequencies, including gamma rays and visible light. Thus, gamma rays from a radioactive source may also be used to expose imaging materials.

Film radiography is the analogue method of presenting observable physical parameters. Digital X-ray imaging presents the information as a matrix of numbers whose value corresponds to the transmission of radiation through the imaging object. Digital images are commonly obtained by exposing reusable phosphorous imaging plates and then scanning the image into digital format. Exposed film may also be scanned into digital format.

Technology Overview: SF_6 Alternatives

For this summary the focus is on SF_6 alternative gases and exclude discussion on other technologies that may also displace the purchase of new SF_6 equipment: For example vacuum breakers.

A number of gaseous dielectrics have comparable or better dielectric performance than pure $SF_{6,}$ but also possess some potential compromises in performance. Four gas candidates are described below.

Trifluoroiodomethane

Trifluoroiodomethane (CF_3I), a gas that is chemically inert and non-flammable; and more importantly, has a dielectric strength that is 1.2 times higher than that of SF_6. The weak chemical bond C-I in CF_3I means that it can be decomposed quickly in the atmosphere, which is one of the reasons that CF_3I possesses a GWP of less than 1 over 100 years. CF_3I has to be used in low proportions as part of a binary mixture with CO_2 or N_2 to reduce the overall liquefaction temperature.

CF_3I is denser than air, which means if a substantial level of CF_3I is released and allowed to settle in an enclosed space, it presents the risk of asphyxiation.

Based on inhalation tests, the U.S. National Research Council's (NRC) committee on toxicology has recommended that CF3I has no observed adverse level (NOAEL) on cardiac sensitization if the concentration is 0.2%, whereas the lowest observed adverse level (LOAEL) is at 0.4% (National Research Council (US) Subcommittee on Iodotrifluoromethane 2002). However, it was also stated in the compressed gas association (CGA) standard that CF3I is a non-toxic gas. Further investigation may be required to provide clearer indication on the toxicity level of CF3I. Since CF3I is proposed only to be used in relatively low proportions as part of a gas mixture in high-voltage equipment, it is, therefore, suggested that the overall toxicity level of the CF3I gas mixture would be drastically reduced when mixed with a buffer gas such as CO2 or N2.

Perfluoroketone Gases, Including $C_5F_{10}O$ (Novec 5110)

Perfluoroketone gases (C_4F_8O, $C_5F_{10}O$ and $C_6F_{12}O$) have extremely low GWP with a dielectric strength up to 2.7 times higher than that of SF_6. However, these gases have a relatively high boiling point. At atmospheric pressure, $C_5F_{10}O$ and $C_6F_{12}O$ tend to liquefy at temperatures of 27°C and 49°C respectively. As a result, $C_5F_{10}O$ and $C_6F_{12}O$ cannot be used at pressures higher than 0.8 bar and 0.3 bar respectively (at room temperature). Although C_4F_8O has a better liquefaction point of 0°C, it is highly toxic and not considered as a viable alternative to SF_6.

ABB uses the Novec 5110 molecule in its product, Airplus. With testing, it was determined to be advantageous to use different carrier gases with C5-PFK depending upon the voltages:

- a mixture of C5-PFK, CO_2 (carbon dioxide), and O_2 (oxygen) is used with high-voltage equipment
- a mixture of C5-PFK, N_2 (nitrogen), and O_2 (oxygen) for use in medium-voltage applications.

Both of ABB's gas mixtures are called AirPlus commercially. They are delivered as a fluid and then vaporized and mixed during the filling process, although ABB is working with various gas manufacturers to see if the gases can be readied off site and delivered to the utilities pre-mixed at the desired rates.

Hydrofluoroolefin

Hydrofluoroolefin gases like HFO-1234ze(E), HFO-1234yf and HFO-1336mzz-Z have a comparable dielectric performance to SF_6 with significantly lower GWP values. As a replacement candidate, HFO-1234ze(E) has two main limitations: (i) a lower dielectric strength than SF_6 (around 85%) and (ii) a higher boiling point than SF_6 at around -19°C. HFO-1234yf cannot be used as a potential SF_6 replacement due to concern of flammability and HFO-1336mzz-Z is practically liquid at room temperature. The key environmental disadvantage of this group of gases is that they decompose in the atmosphere to form trifluoroacetic acid (TFA) which accumulates in nature without decomposing despite possessing low GWP values (Beroual and Haddad 2017). With sufficient number of arcing events, HFO can decompose and generate soot formation. This is an operational concern if the soot accumulate on the solid insulator within the gas-insulated equipment and this conductive layer will inherently reduce the creepage length to flashover.

Fluoronitrile

C_3F_7CN gas, or as commercially known Novec™ 4710, a gas candidate developed by 3M, which can potentially replace SF_6 for high voltage equipment. The molecular structure of C_3F_7CN, or $(CF_3)_2CFCN$. C_3F_7CN has similar properties to SF_6. The physical properties of both gases are shown in Table 2-5 below. As shown in the table, C_3F_7CN is a gas that possesses a higher molecular weight, boiling point and gas density than SF_6. In its pure form, it has a significantly lower environmental impact since it has a much shorter atmospheric lifetime and a GWP of about a tenth of SF_6. It is noteworthy that the GWP of pure C_3F_7CN is still reasonably high at 2,100 but only 4-10% C_3F_7CN is used in the mixture for existing commercial products which represents a 98% reduction in GWP when compared to SF_6. The key difference between the two gases lies in the atmospheric lifetime where C_3F_7CN can decompose within 30 years while SF_6 has an accumulative environmental impact over time.

In accordance to CLP regulation 1272/2008, C_3F_7CN with a LC_{50} (lethal concentration at 50% mortality) well above 20,000 ppm, the gas is classified as practically non-toxic. As with the GWP, the overall toxicity will reduce if C_3F_7CN is used in low concentration as part of a mixture. This strongly indicate that an acceptable personnel safety margin can be achieved in the event of a significant gas release for an indoor substation.

Application Considerations

Application considerations: SF_6 Monitoring

UHF Analysis

UHF analysis (Figure 6-90) provides the following advantages and limitations:

- The technique is well suited for continuous monitoring of SF_6 equipment such as GIS
- Rejection of external noise is relatively straightforward
- Signal location using UHF is possible exploiting both the decay of signal with distance and with time-of-flight measurements
- If the discharges are large enough, the UHF technique can detect discharges in solid insulation. (AE techniques suffer with large attenuation of discharges in solid insulation. For these types of discharges, UHF may be the only technique that could measure the signals).
- The UHF coupler can measure discharges approximately 30ft either side of the coupler. This allows for economical deployment of a reasonable number of couplers for complete GIS coverage
- A challenge is that multiple signals are difficult to characterize and locate

Figure 6-90
UHF being applied in the field. In this case, coupling was via a barrier since there were only a few window ports.

Acoustic Emission (AE) Diagnosis Monitoring

The AE technique (Figure 6-91) provides the following advantages and limitations for monitoring of SF_6 equipment:

- The AE signals decay rapidly from the source. This allows for accurate location of the source of the AE.
- The AE signals are different in nature for different types of discharges - allowing for some insights into what the defect may be.
- The AE technique is especially sensitive to moving or bouncing particles. This makes the AE technique especially valuable during GIS commissioning - and the first few months - as that is when particles are most likely to create problems.
- If a GIS does not have any way to extract UHF signals (e.g. couplers or windows or exposed barrier boards) then the AE technique is an approach to try and locate and identify discharges.
- A challenge is mechanical noise can mask AE signals from PD.
- A further challenge is solid insulation attenuates AE signals rapidly, thus often preventing AE from PD inside solid insulation from being detectable.

Figure 6-91
Acoustic Emission (AE) being applied to a section of GIS bus.

Chemical Analysis

For SF_6 monitoring, chemical analysis provides the following advantages:

- While there are unstable by-products that disappear with time, there are also stable, long-lived by-products. Detection of these stable by-products can give an insight into problems that may have occurred internally over a long period of time. This is an advantage because discharges can be intermittent, so the ability to see back in time to what was happening is a help.
- Locating a problem is often possible to within each gas zone since most zones don't have gas lines to adjacent zones.

There are some important limitations to bear in mind when applying this technique:

- Some gas compartments have long filling lines. To get to the true sample it would be necessary to bleed these filling lines. Depending on the size of these filling lines, this may result in excessive gas loss.
- Some gas compartments have gas lines that join adjacent zones. This results in dilution of the by-products and reduces the ability to accurately pin-point the location of the problem.
- Any gas compartment that has switching in it (breakers, isolators, grounding switches) produce by-products as a part of normal operation of the equipment. These by-products will be difficult to discriminate from those produced by an internal problem such as sparking, corona or overheating.

- An added complication is that breakers (and sometimes other compartments in GIS) have absorbers installed to scavenge by-products and moisture. These absorbers will also scavenge the by-products produced by sparking, corona and overheating - hence masking the problem.

Despite these limitations, the chemical analysis technique has been used effectively to locate numerous problems on site. The key is to understand the limitations and only draw conclusions where they are unambiguous—e.g. high by-product levels in a non-switching section of GIS bus are a cause for concern, especially if the levels continue to rise over time.

X-Ray Imaging

X-Ray analysis (Figure 6-92) provides the following advantages and limitations:

- Ability to image internal components can provide information about the condition of key components without dismantling
- Ability to locate broken insulators of other components after a failure
- Provide information about some failure modes
- A challenge is the setup requires experimentation with exposure levels and viewing angles
- A challenge is radiation involved so safety precautions need to be taken
- A final consideration is that the technique is susceptible to vibrations

Figure 6-92
An example of a digital X-ray system deployed. The radiation source is the blue cylinder to the right. The digital X-ray plate is the red target to the left.

Application Considerations: SF_6 Alternatives

For any new dielectric, safety and reliability should not be compromised during implementation. Open questions exist for the industry with SF_6 alternatives. Answers to the questions are being developed through the following actions:

- Develop and share a full understanding of what SF_6 alternative technologies exist and are emerging
- Research and compile the technical details of the different SF_6 alternatives
- Track and share the applications of SF_6 alternative technologies in the industry
- Document field experiences from the application of SF_6 alternative technologies in the industry
- Perform laboratory experiments to address open industry questions on SF_6 alternatives.

Readiness of Technology

The monitoring technologies summarized above are commercially available, but important questions remain regarding their performance with GIS/GIL. For example, interpretation of partial discharge signals is always complex and often requires multiple technologies to be applied to the problem to come to an estimate of the risk. Such questions can be most effectively answered within the controlled environment provided by a GIS laboratory. Once a GIS/GIL is in service there is very little experimentation possible on that critical apparatus, whereas a laboratory allows a wide range of "what-if" questions to be addressed.

In terms of SF_6 Alternatives there is a wide range of readiness that is a strong function of the technology and the voltage and current interruption rating. For the SF_6 alternative gases described in this summary there are no deployments in the US yet. There are many examples of deployments elsewhere in the world.

Field or Testing Results

SF_6 Monitoring

Testing results are being gathered by, for example EPRI, which has constructed and commissioned an SF_6-filled GIS laboratory in Charlotte, NC. The laboratory provides valuable learning in reducing operations and maintenance (O&M) costs through optimized maintenance, improved insights into equipment condition, improved reliability of SF_6 equipment through early warning of emerging problems, and guidance on the optimal selection and interpretation of on-line monitoring equipment.

Figure 6-93 shows the SF_6 laboratory and its key components.

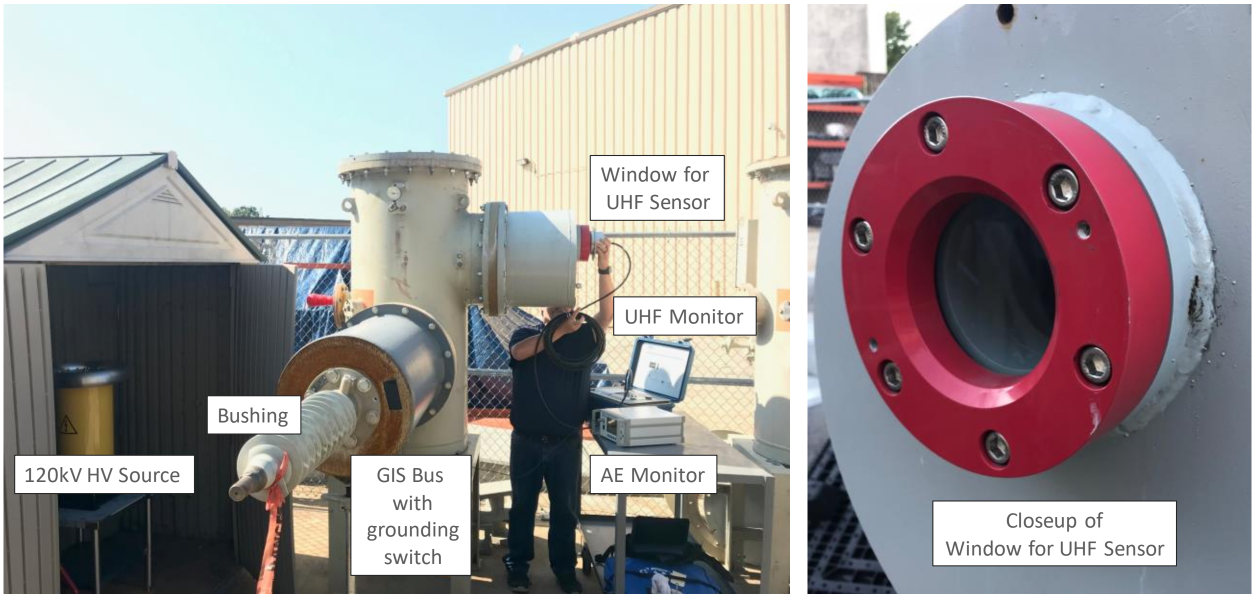


Figure 6-93
SF_6 Laboratory commissioned in Charlotte, NC

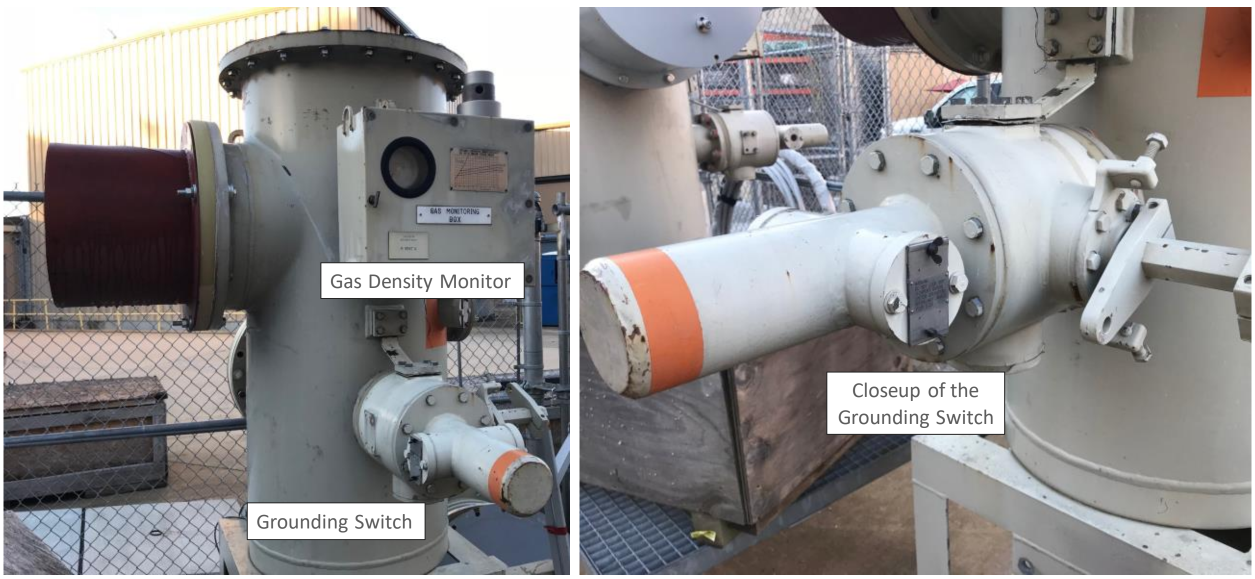


Figure 6-94
SF_6 Laboratory. Rear view.

Figure 6-94 shows the rear view of the SF_6 test setup. It shows the gas density monitoring unit and the grounding switch. The research plans call for the introduction of partial discharges in the GIS. One approach to introduce a variable and controllable partial discharge source will be to fit one of the contacts on the grounding switch with a sharp needle. In that way the gap between the needle and the ground will be able to be adjusted externally via the grounding switch controls.

For SF_6 Alternatives, it is of primary research value to understand which SF_6 alternative technologies are being applied in the field, and what lessons are being learned from these deployments. This is especially true for utilities in the US since deployments to-date have been outside of the US. There is thus a valuable opportunity to learn from the existing pilots. EPRI, for example, is tracking these industry deployments and field deployments.

Vendor Landscape

For SF_6 replacements, the vendor list is not a full list of all possible vendors but would include GE, ABB/Hitachi, Siemens and Mitsubishi. For condition monitoring, a landscape would include DOBLE, Qualitrol, Omicron, ABB, Siemens, Lumasense, Vaisala etc.

7
DEVELOPMENT OF FORUM AND EVALUATION PLAN

The ATWG has developed plans for the potential forum, venue and tools required for this analysis work; and has recommended a plan to vet new technologies for potential analysis. As part of this section, the working group is providing some high-level recommendations for better planning the investment in and implementation of new technologies for the New York state electricity grid. The following three items are of great value in the evaluation and coordinated implementation process:

Operation of a Joint Utility R&D Advisory Working Group

As transmission and distribution grids are evolving, it is becoming increasingly evident that the grid operates in an integrated manner. In an environment like NY, where a highly interconnected electricity grid is owned by several transmission owners, proper coordination among all these stakeholders is needed to optimize the grid operation and performance. This also applies to the deployment of advanced technologies, especially the ones that are utilized for improving the power system operation and control. Many of these technologies only provide their true value and maximum potential if deployed strategically in a coordinated way. For New York to be able to more effectively utilize and adopt new technologies, it is, therefore, of high importance to maintain proper coordination among all relevant stakeholders on this topic. This will allow new ideas to be thoroughly discussed and evaluated from a holistic perspective, identifying the best use cases for them, which can provide maximum value to the grid overall. It will also allow for pilot or demonstration projects as well as the coordinated optimal deployment when a technology reaches a potential implementation stage.

A second significant benefit of an ongoing advisory working group is the continuous exchange of information between transmission owners and other stakeholders in a more comprehensive and formalized way. This will lead to sharing experiences with specific technologies or products, therefore avoiding duplication of effort leading to similar learnings or mistakes. Coordination would also avoid duplication of research resources and funds. When it comes to new technologies and ideas, it is important and valuable to have some initial joint R&D efforts until a technology is brought to a fairly mature level and could then be adopted up by entities who are more interested in it or get the most value out of it for actual implementation and deployment. Such an advisory group could coordinate such initial research and development stages.

Consequently, this collaborative process will result in improved prioritization of R&D work, better focus on technologies that provide value to the overall grid, and therefore, overall a more streamlined and optimized decision and investment making process in NY's roadmap for adopting and utilizing new technologies for successfully achieving its CLCPA goals.

Creation of a Research and Development Venue

In many cases, appropriate evaluation of new technologies cannot be performed only by literature surveys, shared experiences, or developer/vendor information. Specific grid details or requirements might make it difficult or inaccurate to extrapolate performance and benefits based on experience from others. In such cases, further specific studies or demonstrations are needed to appropriately evaluate a technology and obtain more confidence in it. Given that actual field demonstrations are often complex and risky, realistic studies, tests, and demonstrations taking place in a controlled laboratory environment provide a very good alternative to experiment with and further develop new technologies. This approach has been successfully used in many other places worldwide, such as in Europe,[13] Asia[14, 15], and Canada[16, 17]. Such a laboratory environment should have several key features and provide key capabilities that would allow stakeholders to properly experiment, study, test, and evaluate new ideas and technologies in an accurate and realistic way and also allow them to gain experience working with them and operating them prior to field deployments. Some crucial capabilities include, at a high-level:

- The venue should provide a collaborative environment where utility personnel can work with various other stakeholders as well as technology providers.
- The venue should have research, development, and testing capabilities spanning a wide area of technologies that relate to the electricity grid operation at all levels (transmission, sub transmission, distribution).
- The venue should provide a large variety of analytical and physical tools that would allow people to run studies and experiment with software or hardware equipment and new apparatus or techniques.
- The venue should provide a variety of modeling and simulation tools and capabilities that would facilitate studies and experimentation. Such tools should be using actual grid models and data that can mimic the reality as much as possible. In order for such an environment to be useful and successful such models should be kept up to date and provide a high-fidelity representation of the grid at various levels and domains to support a variety of different studies.
- The venue should have the capabilities, policies, and processes in place to appropriately secure confidential data and ensure proper utilization of such data accordioning to utility and governmental policies and guidelines.
- The venue should have enough space and other capabilities to accommodate demonstration and testing of larger-scale hardware equipment. Such a lab should go beyond performing traditional model based studies and should be able to provide capabilities to test software and equipment in set ups as close as possible to real field conditions, providing capabilities for new system configuration, preliminary commissioning testing prior to moving to the field commissioning, as well as training for personnel on the actual equipment in a safe lab-based training environment. The venue should be able to support such equipment configuration, commissioning, and training needs for new technologies.
- The venue should be able to serve as a "one-stop shopping" location, where new technology developers and vendors can reach out to the entire group of NY electricity grid stakeholders and present their ideas for a more collaborative and coordinated discussion and evaluation.

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[13] https://www.hvdccentre.com/

[14] https://www.kepri.re.kr:20808/newEng/index

[15] http://eng.csg.cn/Press_release/News_2019/201909/t20190916_303623.html

[16] http://www.hydroquebec.com/innovation/en/institut-recherche.html

[17] http://energymanitoba.com/partners-members/manitoba-hvdc-research-centre/

Development of such an environment would allow NY stakeholders to work more closely together and seek collaborative solutions to common issues, avoiding duplication of investment and effort, in particular at earlier R&D stages. It would also provide NY utilities a controlled environment that they can experiment and test (or even to some extent develop and expand) new technologies without having to solely rely on vendor or other third-party information and experience. Such an environment could also be leveraged by manufacturers or renewable energy developers for some of their more detailed and advanced studies, potentially resulting in reduced project development costs.

Coordinated Technology Evaluation Plans

Based on the above two items, a coordinated pilot implementation plan can be devised for a potentially useful new technology. The plan would approximately follow the high-level process presented below:

- A new idea or a new technology is proposed as a solution for addressing one or more specific issues on the NY grid resulting for CLCPA goals.
- The idea is presented and discussed in the joint utility advisory working group.
- Utilities discuss any knowledge or experience that they may have with this technology and potentially seek input and information from vendors or other entities or utilities outside NY.
- If the idea is deemed of interest and value by some of the NY utilities and is seen as having good potential for benefiting the NY grid, a study or a lab testing and demonstration project is defined to further evaluate the technology in a more systematic way and its applicability and benefit for the NY grid.
- Based on the lab evaluation, if the idea is determined as viable for moving forward, a preliminary plan for pilot implementation(s) is created and a cost/benefit analysis is performed. Lab testing can be used to assist, facilitate, and de-risk the specific pilot implementation.
- Based on the pilot outcomes, the idea/technology is picked up by the entity or entities that are more appropriate for implementation and large-scale deployments, either based on the fact/estimation that they get the most value of this technology, or based on the fact/estimation that implementation in their system(s) would provide the most benefit for the grid. At this stage deployment of this technology becomes a regular utility project that follows all the existing or updated implementation policies and procedures.

The Advanced Grid Innovation Laboratory for Energy (AGILe)

The Advanced Grid Innovation Lab for Energy (AGILe) is an initiative of the New York Power Authority that could be leveraged to fulfill expeditiously and cost-effectively many of the needs identified in this section. The concept of AGILe originated in late 2012 addressing some of the items identified in the New York Energy Highway Blueprint[18]. It was conceived as a collaborative R&D environment and laboratory facility in which electric utilities and other stakeholders of the electricity industry in New York and nationwide could work together along with academia, research centers, and technology providers in addressing various grid challenges

[18] https://www.smartgridlegalnews.com/wp-content/uploads/sites/517/NY_Blueprint_FINAL_3.0.pdf

and experiment with innovative technological solutions. After extensive benchmarking efforts and coordination with various New York stakeholders, NYPA proceeded to construct a small-scale, proof-of-concept facility to demonstrate and evaluate the value such a facility could provide to New York and the electric power industry overall.

AGILe is currently a power systems laboratory, with a simulation and testing facility, which was established in 2017 as a collaborative initiative lead by NYPA and supported by a number of additional stakeholders. The lab is able to provide electric utilities, governments, universities, high-tech businesses, and others, from around the world, with a wide range of research and development tools. The research work performed in the lab could support R&D efforts and fast track commercialization and adoption of new technologies, by serving as a realistic testbed for demonstration and experimentation with innovative ideas and products. As such, AGILe could accelerate improvements to New York's energy infrastructure and lead to a cleaner, more reliable, and more efficient electric grid. General research areas of relevance to AGILe include:

- advanced transmission and distribution applications,
- cyber security,
- substation automation,
- sensors, and
- power electronics controllers.

At this initial stage, AGILe is located at the White Plains offices and primarily comprises a digital real-time grid simulation lab, which will enable real-time simulations of New York State's electrical grid. It is initially targeting transmission- and distribution-level research focusing on power system wide-area monitoring and control, synchrophasor applications, renewable energy integration, and substation automation and control. It has the potential to provide grid benefits, such as accelerating and streamlining deployment of new equipment and technologies, recreating and analyzing events and phenomena, incorporating intermittent resources, and improving grid reliability and control.

Since its establishment, AGILe has gradually expanded in terms of core capabilities and functionality. The real-time grid simulators systems were initially sized to be able to simulate in real time the entire New York state bulk power grid in both the full three-phase transient simulation domain and the positive sequence, dynamic simulation domain. Some of these capabilities have since expanded to allow for even more detailed modeling. The systems include a large number of analog and digital I/Os and support several digital communication protocols for interfacing the simulators with external devices for software- or control-hardware-in-the loop testing. For the same purpose, the lab is equipped with a number of amplifiers to provide the appropriate voltage and current signal levels for the external connections.

One of AGILe's main goals is to develop realistic models of New York's electricity grid that can be utilized as the basis for technology development, demonstration, and evaluation. A crucial impediment to the adoption of new technologies in the electric power industry lies in the difficulty of deploying them in the field, as this is typically time consuming, complicated and risky. Thus, given reliability constraints, unless the technology is proven and mature, electric utilities are reluctant to implement pilots, let alone wider deployments. At the same time, most of the academic research and development, although future looking and cutting edge, is typically performed using simplistic models and synthetic data. Therefore, a disconnect exists between what is theoretically developed by research entities and what is applied in practice, leading to very long lead times for a new idea to find its way to a commercial implementation.

In an attempt to narrow this gap, AGILe plans to build and maintain accurate and realistic models of the electric power grid of New York and create test beds researchers can use to demonstrate their technologies under conditions that are as close as possible to real field conditions, without the time, complexities, costs, and risks of an actual field implementation. This approach de-risks such new technologies for the electric utilities, which can now more confidently proceed to field pilots and field installations after having set up and extensively tested new apparatus and algorithms in a realistic lab environment. AGILe's collaborative model with the engagement from all New York utilities, as well as the NYISO, as opposed the single-entity lab model, provides a unique opportunity for achieving such goals.

The lab also focuses on two other key capabilities: modeling and simulation of communication systems and cyber security events as well as production cost modeling and analysis. The first is implemented via a commercial-grade network emulator and provides a versatile environment that allows a more realistic representation of cyber-physical systems. It enables evaluation and testing of grid monitoring and control schemes taking into consideration the performance of the communication network these schemes rely on by co-simulating the network along with the power grid. The latter relies on a small-scale high-performance computing (HPC) implementation of production cost simulation software and is intended as a means of economic evaluation of new technical solutions, allowing AGILe to assess not only the engineering but also the economic impact of new technologies to the grid. The lab is also equipped with more traditional offline grid simulation and data analysis tools providing cutting-edge capabilities for research, analysis, and development in the electric power industry.

In summary, it is expected that the lab will help deliver, among other things, the following capabilities and outcomes:

- Advanced modeling of power grid components
- Real-time simulations of New York State's electrical system
- Hardware-/Software-in-the-loop equipment testing
- Emulation and performance characterization of power grid data communication schemes
- Automated controls to improve network resiliency, security, safety and efficiency
- Integration of large-scale renewable energy resources as well as distributed energy resources
- High level of situational awareness to enable optimal grid operation under various conditions

Since its establishment AGILe has not only successfully allowed NYPA engineers to test emerging technologies on a digital model of the grid before putting them into the real world, but the lab has also fostered many industry-first collaborations. AGILe is being operated in close collaboration with the Electric Power Research Institute (EPRI) and is being leveraged as a resource by a number of EPRI projects. In addition, the lab has established partnerships with a variety of academic institutions, both in NY and nationwide, other research organizations and laboratories (such as National Labs, including the Brookhaven National Lab and the National

Renewable Energy Lab), as well other utilities and vendors (e.g. EirGrid and ESB of Ireland). AGILe is participating in active research projects with all these partners.

Research labs are gaining popularity with electric power utilities and are being viewed as a valuable asset to help plan and prepare for the fast-changing landscape of the electricity industry. AGILe's vision expands more than the technical and engineering aspects of a lab and also looks into creating a collaborative research environment that brings people from utilities, academic institutions, technology vendors, and research organizations together to work on common challenges and opportunities that can improve the performance, effectiveness, and efficiency of the electricity grid.

In particular, the value of AGILe lies in the vision that the lab can:

- Perform specialized grid studies with powerful modeling and simulation tools, which are not typically done as part of regular processes.
- Offer a variety of modeling, simulation, and analysis tools including both leading real-time grid simulation systems (RTDS and OPAL-RT) for realistic hardware- and software-in-the loop testing and demonstration of equipment prior to field deployment.
- Utilize actual data and models to provide realistic and flexible test beds to accelerate development, adoption, and commercialization of new technologies at both transmission and distribution levels or within microgrids.
- Present both an industry and academic collaborative environment to leverage technical capabilities and expertise from diverse participants.
- Offer "one-stop shopping" for external entities (including researchers, vendors, or other technology providers) with participation from all NY stakeholders for accelerated research, development, and deployment opportunities in New York.

To completely fulfill this vision and provide the expected value, AGILe will eventually need to move from its current, proof-of-concept phase to become a stand-alone research facility, with expanded laboratory equipment and capabilities, functioning under a fully-collaborative sustainable operating model.

8
COST BENEFIT ANALYSIS

A Benefit and Cost Analysis (BCA) of any Research & Development (R&D) project should consider both quantitative and qualitative factors to make a base case for the investment. It should also compare similar projects to determine the potential benefits, risks, and likelihood of success. A BCA should be conducted before allocating funds to any project. A thorough analysis of a project should identify all potential benefits and the probability of achieving goals, compared with the all-in associated costs. The outcome of the analysis should help decision makers determine if the project is feasible and if it should proceed, or if the funds are better spent elsewhere. If a project is to go ahead, the benefits should be compared to the costs and meet the intended goals. A thorough BCA should identify the purpose and goals behind the project, gather business and project requirements, identify all of the resources to be used, determine the metrics to measure success, and consider other potential options.

The New York State investor owned utilities have developed a BCA Analysis Handbook that is a framework made from the February 26, 2015 Order Adopting Regulatory Policy Framework and Implementation Plan that a determination that since the Reforming the Energy Vision (REV) is a long term, far reaching initiative that will eventually touch most parts of the utilities' infrastructure and business practices, an attempt to project a quantified analysis on the wide-ranging set of potential benefits in a REV approach, against hypothetical future cost scenarios under both REV and conventional approaches, would be artificial and counter-productive and that such an effort would distract from the far more important task of carefully phasing the implementation of REV so that actual expenditures, when they occur, are considered intelligently in light of potential benefits recognizing that in this multi-phased implementation process, benefits and costs will be considered with increasing specificity. The NY utilities have prepared their BCA Handbook to provide a foundational methodology along with valuation assumptions to support a variety of utility programs and projects. Their BCA Handbook were issued with the expectation that they will be revised and refined over time and as informed by new opportunities that REV provides, experience gained from programs and project deployment, and experience gained from their transmission and distribution grid system enhancement. The Handbook typically covers the following four categories of utility expenditures, as required per the BCA Order, investments in distributed system platform (DSP) capabilities, procurement of distributed energy resources (DER) through competitive selection, procurement of DER through tariffs, and energy efficiency programs. The Handbook was prepared consistent with the BCA Order list of principles of the BCA Framework. These five principles stated that the BCA Handbook should establish the BCA Framework, be based on transparent assumptions and methodologies, list all benefits and costs including those that are localized and more granular, avoid combining or conflating different benefits and costs, assess portfolios rather than individual measures or investments (allowing for consideration of potential synergies and economies among measures), address the full lifetime of the investment while reflecting sensitivities on key assumptions, and compare benefits and costs to traditional alternatives instead of valuing them in isolation. Given these principles and framework guidance, the purpose of the BCA Handbook is to provide the methodology for calculating benefits and costs of their programs, projects and investments using the input assumptions as provided within and/or referenced to external sources.

The Transmission Policy Working Group has developed recommended changes to their BCA framework for their transmission projects that proposes a BCA approach that can be applied to the full range of potential local transmission and distribution projects that have the potential to unlock Climate Leadership and Community Protection Act (CLCPA) benefits. The methodology is focused on additional CLCPA-related metrics, and uses a simple, easily repeatable methodology that would include a combination of metrics enhances and understanding of project contributions to CLCPA. These objectives would include a BCA to establish relative cost-effectiveness, net benefits to capture the scale of benefit achieved, and incremental cost of additional hosting capacity to evaluate distribution projects. Key preliminary recommendations being considered are, the commission accepting the proposed transmission related BCA guidelines for CLCPA projects, and the simple, consistent, repeatable BCA guidelines to allow a transmission owner to efficiently prioritize its CLCPA-related investments.

The Department of Energy (DOE) (see Appendix B) developed guidance for evaluators who conduct impact assessments to determine the economic benefits and costs, energy benefits, environmental benefits, and other impacts of the Office of Energy Efficiency and Renewable Energy's (EERE) R&D projects. The impact assessments covered in their guide are intended to address the following questions of interest to managers of DOE, Congress, the general public, and other stakeholders: To what extent has the project produced energy and economic benefits relative to the next best alternative? To what extent has the project achieved environmental benefits, and enhanced societal benefits? To what extent has the project cultivated a knowledgebase in the research community that has impacted innovations in today's markets? Would today's commercialized technologies likely have happened at the same time, and with the same scope and scale, without the project efforts? Was the public investment worth it? In addition to energy and economic impacts, the approach should quantify emissions reduction, environmental and other health benefits, health cost avoidance, energy policy benefits, and knowledge creation and diffusion. It addresses attribution of benefits through the use of the counterfactual model which seeks to compare outcomes with what would likely have happened in the absence of the R&D project. The method presented in this guide builds on the R&D impact assessment approach used by the National Institute of Standards and Technology (NIST) and improves on the approach employed by the National Research Council (NRC).

A study completed by several European agencies (see Appendix B) that explored the BCA of R&D projects found that the use of BCA to evaluate these types of projects have often been hindered by the intangible nature and the uncertainty associated to the achievement of R&D results. The core of their BCA is an evaluation of the project socio-economic benefits and costs. The net effect on society is computed by a quantitative performance indicator (the net present value, or the internal rate of return, or a benefit/cost ratio). In line with the general BCA fundamentals, a BCA model of these type of projects should make use of; shadow prices to capture social costs and benefits beyond the market or other observable values; a counterfactual scenario to ensure that all costs and benefits are estimated in incremental terms relative to a 'without project' world; discounting to convert any past and future value in their present equivalent; and a consistent framework to identify social benefits by looking at the different categories of agents (producers, consumers, tax payers, rate payers). The project evaluations are dividing social benefits in two broad classes. The first is benefits accruing to different categories of direct and indirect users of the infrastructure services, such as firms benefitting from technological spillovers, consumers benefitting from innovative services and products, and the general public. The second is the identification of use-beneficiaries that is project specific reflecting the social value of the discovery potential of the research project.

It would be the goal of the Advanced Technology Working Group to coordinated and evaluate all BCA options for each R&D project pursued in this effort and continue to improve on these BCA methods as new and underutilized technologies are being evaluated in New York State.

A
R&D PROJECT LISTS

Project Synopsis - NYSERDA

Rensselaer Poly Inst 112721 — Control Equipment Performance Monitoring utilizing PMUs

The main objective of this research study is to advance the state-of-the-art application of Phasor Measurement Unit (PMU) data, allowing the monitoring of dynamic performance capabilities of control equipment (ex. generators, flexible alternating current transmission devices, etc), which are critical to the operation of the New York State (NYS) electric power grid. The investigation of the performance of such equipment has traditionally been done during equipment commissioning and outages. Using PMU data, it is possible to provide continuous monitoring of the performance of such equipment in real time, during non-disturbance and disturbance conditions and utilize this information to improve operations of the NYS electric power grid.

NYPA 112759 — Advanced Stability Controls

This engineering study will quantify the costs and economic benefits of the Multi-Functional Multi-Band Power System Stabilizer (MF-MBPSS) based closed-loop control of a limited number of shunt-connected Flexible AC Transmission Systems (FACTS) devices and Power System Stabilizers (PSSs) that can improve the dynamic performance of the New York State electric transmission grid and even that of the Eastern Interconnection as a whole, under a set of critical contingencies and network conditions. This project will assess the economic value of a full-scale deployment of the technology on all applicable NYPA assets, using optimized and coordinated parameters determined according to New York Independent System Operator (NYISO) operations planning rules. Using a comparison with baseline values derived from alternative solutions, NYPA intends to quantify operational benefits of such technologies while elaborating credible deployment pathways with growing complexity and benefits. The project will investigate the technical feasibility of a specific use case of the proposed closed-loop controls using Electro-Magnetic Transient Program based Software-in-the-Loop simulation of NYPA network model with embedded Simulink models of Intelligent Electronic Devices (IED), PMUs and other control devices that meet NYPA functional requirements.

Quanta Technology 118219 — NY State-Wide Area Protection Study

In this Wide-Area Protection Study (WAPS), Quanta Technology, along with its partners the New York State Reliability Council (NYSRC), New York Independent System Operator (NYISO) and participating New York State Transmission Owners (TOs), plans to expand on the work of previous studies to develop new and improved mitigation measures that are also feasible for near-term field implementations. The MDMS2 will assess the feasibility of implementing the mitigation measures in a New York State wide-area protection and control system (WAPCS) that will leverage the Phasor Measurement Unit (PMU) system already deployed in New York State to enhance the reliability and resiliency of the New York electric power system during major disturbances. In the course of these activities, MDMS2 will focus on improving current dynamic power system models to include inverter-based renewable resources, developing dynamic simulation cases to represent expanded wider range of disturbance scenarios, investigating the New York State power system's responses to such disturbances, developing instability detection algorithms based primarily on PMU measurement data, development of mitigation measures for containing the impact of the disturbances, and verifying the effectiveness and feasibility of the candidate mitigation measures through power system dynamic simulations.

SUNY Albany 118222 — Development of a Extreme Wind Forecasting Tool

The objective of the proposed work is to develop the Wind Extreme Forecast System (WEFS), to forecast probabilities of threshold wind speeds and wind gusts that may produce power outages on local to regional scales (transmission down to distribution lines). WEFS will be based upon state-of-the-art numerical weather prediction (NWP) modeling combined with machine learning techniques that will produce high spatial (1 km) and temporal (15 minutes to 120 hours) resolution forecasts that will enable utilities and other stakeholders (e.g. emergency management services) to plan for and deploy necessary resources to minimize power outage impacts, resulting in improvements to reliability and resiliency of the power distribution system.

Quanta Technology 118220 — Central Hudson Energy Storage Study

In this research and development project, Quanta Technology, along with its partner Central Hudson Gas & Electric (CHGE), plan to develop a set of energy storage guidelines and procedures to facilitate economic integration of renewables into the New York State transmission and distribution (T&D) system. Properly sited and sized storage can not only defer T&D capital investment, but it can also facilitate more efficient grid management. This project will further the goals of the New York State Energy Plan, Clean Energy Standard (CES), and the Reforming the Energy Vision (REV) initiative.

Rochester Data Science Consortium 137935 — Advanced Modeling of Power System Dynamics Using Machine Learning

Accurate and validated device models are essential for reliable and economic power system operations. Many critical tasks, such as selecting operating limits and planning studies for assessment of new generation and load growth rely on having an accurate device model. North American Electric Reliability Corporation (NERC) Reliability Standards require that power flow and dynamics models be provided for all devices in operation. More specifically, NERC requires models for all generators in North America with capacities larger than 10 MVA to be validated every five (5) years (fine-tuned every year). However, manufacturer-specific dynamic models commonly provided for interconnection studies are not adequate for regional planning. Accurate models and modeling tools become a crucial need for stabilizing the grid and preventing unplanned outages or blackouts. This project includes the performance evaluation of two different machine learning (ML) approaches, i.e., Deep Learning and Reinforcement Learning for synchronous machine model parameter verification. One for steady state parameter tuning and the latter for dynamic parameter updating. The performance of the two (2) approaches will be evaluated under different operational conditions and complicated scenarios using simulated data and if possible, real world data. The approaches can potentially provide more accurate models, overcome many shortcomings of existing practices, and improve the scalability, usability, and efficiency of the current model validation process used by the industry.

Optimal Solutions 137938 — Real Time Analysis of Transformer Oil

In this technology feasibility study, Optimal Solutions and its partner New York Power Authority will investigate developing a new online transformer oil analysis system which is designed to measure dissolved gases in transformer oils to predict potential transformer failures. Optimal Solutions proposes to leverage new emerging micro-electro-mechanical based near infrared detectors, new optical sensors, and new machine learning technologies to design a compact and cost-effective system that is robust, accurate, and reliable. The system will also be designed for online use and continuous operations and will allow utilities to achieve continuous monitoring of their transformers health via online / real-time dissolved gas analysis to help them avoid costly and catastrophic transformer failures.

NYPA 137940 **Model Translation Tool**

The objectives of this project is to develop meta-modeling syntactic and semantic mappings able to capture and represent all the information currently used and fragmented in multiple specialized power system analysis tools. Developing model interpretation technologies, specifically applicable to power systems, can enable model portability between tools and different tool versions through a software interpreter. The interpreter will be able to perform operations on models, called model transfomations, which would enable merging, aligning, refining, and translating models. Project objectives also include deriving model transformation methods that can be applied in order to synthesize specialized models for power system dynamic simulations; deriving re-usable and composable equation-based models of power system components using standardized modeling languages and standardized model-exchange technologies; building models with different testing scope, to evaluate the developed methods and technologies, and to be re-used in the development of production models for the operation of the New York State electric grid.

NYPA 137941 **Low Frequency AC Transmission Study**

The project objective is to investigate the concept that transmission line operations in low frequency could improve asset utilization and relieve transmission congestion problems by allowing more power through transmission lines without causing instability issues. This study will involve the evaluation of system level and converter level analysis. At the system level, simulation studies will be performed to model and explore operational benefits of LFAC in the transmission network. At the converter level, the proposed study will lead to design of a converter and control strategies required for vendor adoption and potential field demonstration of this concept.

USI 137946 **Underground Cable Advanced Monitoring and Diagnostic System**

In this product development and demonstration project, the Contractor and its partner NYPA will investigate the development of a new underground cable monitoring and diagnostic system to prevent potential transmission cable failures and oil system leaks. The Contractor will utilize new technologies to enhance their existing products and design a cost-effective underground cable monitoring and diagnostic system, to include cathodic protection and dissolved gas analysis, resulting in a more robust, accurate, and reliable system. The online system will allow utilities to monitor distributed cathodic protection and dissolved gas content of their underground transmission cable through the analysis of real time data. The Contractor and NYPA shall demonstrating this new technology in one of NYPA's underground transmission cables.

NYPA 137951 **Deep Learning Computing System for Grid Operations**

In this research study, the Contractor and RPI will investigate developing a new machine learning-based software tool and system for resilient grid operations through improved operator decision support. Machine learning in combination with both phasor measurement unit and simulation data will result in a novel approach not available in any existing industrial solution for the power grid operations. This project focuses on how to apply existing results and technologies from machine learning into power systems, both in terms of selection and training of algorithms and the re-purposing of existing software tools. The overall project objective is to establish the basis for a new innovative machine learning technology to improve the electrical power grid resiliency and its economic impacts in New York State. It is expected that after the initial research phase, the Contractor will be able to deploy and demonstrate the solution together with other utility partners in New York State.

Bigwood Systems 145591 **Sub-Synchronous Oscillation Screening & Mitigation**

This study seeks to screen and identify sub-synchronous oscillations (SSO) that may exist in a network due to the interaction of long-distance transmission systems having series compensation with generators, wind turbines, and other control devices. Bigwood System Inc. will perform topology screening and identification of sub-synchronous oscillations and its subset events. Once identified, the study will perform a full time-domain analysis to identify vulnerable scenarios and determine advisory control adjustments and suggestions for mitigation. The project aims to use SSO analysis to quickly identify and mitigate any potential problems before real damage to any parts of the generation and transmission systems occurs.

Manifold Robotics 145644 — **On-board Power Line Detection, Avoidance, and Tracking for Aerial Drones**

As part of their grid modernization efforts in New York State, electric power transmission and distribution companies are increasing their usage of unmanned aerial vehicles (drones) to facilitate and improve the inspection of transmission lines. This product development project will enable aerial drones to detect power lines using their electromagnetic fields, and either avoid or autonomously track them beyond visual range for inspection purposes, significantly expanding their use to help ensure grid resiliency, reliability, performance, and efficiency. This project plans to develop this technology to become part of the drone's navigational system and not part of its inspection systems.

Switched Source 133528 — **Balancing Phases in Medium Voltage Systems**

This project includes product development and beta deployment for a new power electronics device that balances three phase power flow. This new technology will increase the efficiency of the grid, energy losses in the distribution grid in NY and will also allow for more single-phase renewable generation to be connected to the grid. This work will be performed in a new engineering office that Switched Source will open in New York in conjunction with researchers at a New York university.

Micatu 133658 — **69 kV Optical Voltage/Current Sensor Platform for Sectionalizing Applications**

Micatu is proposing to develope with Hubbell and National Grid, a sectionalizing controller module designed to work with the Micatu m410 Modular Optical Sensor Platform. This would enable existing users of Micatu sensing products the ability to add sectionalizing and Fault Location Isolations and Service Restoration (FLISR) functionality to installed sensor locations by simply installing the four-bay module solution. Currently Hubbell holds the majority market share of all 46kV to 72kV voltage class for sectionalizing control and switching products. Micatu's partnership with Hubbell enables a clear path to commercialization for both new and retrofit installations. Initial plans are to manufacture and distribute this solution in New York State and roll out nationwide based upon successful qualification by a New York utility (National Grid).

SUNY Albany 137936 — **Control of Grid Interface Inverters for Distributed Power system Stabilization**

Higher penetration of inverter based distributed energy resources will present increasing challenges to the stability of the power grid. With more renewable resources replacing traditional generation, there is a reduction of inertia of the power system and with the intermittency of the renewable resources, power fluctuations that impact the system stability can occur if there are insufficient spinning reserves. To connect to the power grid, inverter based distributed resources rely on phase locked loop to capture the grid frequency, therefore without a radical change in control method, they can lose stability in a low inertia system. To mitigate this issue, a new device called virtual inertia can be used which can quickly absorb or release active power to and from the grid. A virtual inertia is defined as the combination of power electronics converter, energy storage device, and proper control algorithm. Addition of the virtual inertia improves the frequency response by reducing frequency deviation and rate of change of frequency. The New York Reforming the Energy Vision initiatives call for solutions that are more environmentally friendly and improve the resilience of the power grid. To that end large-scale renewable energy resources and energy storage will become more prominent in the composition of NY power grids. The proposed control methods in this project will enable integration of the distributed resources while maintaining a grid stability that is comparable to that of traditional generation with guidelines on defining distributed resource sizing and locations for different regions of the power grid. In this project a new control method for grid interface inverters or distributed energy resources is proposed. The proposed method combines the features of grid-forming droop control and virtual synchronous machine control concepts. The proposed approach can be deployed on a wide range of inverters (starting from single phase inverters to large multi-megawatt inverters). University of Albany and Key Capture Energy will evaluate develop robust inverter control methods to improves the stability of grid with high penetration of inverter based energy resources, optimal sizing and structure of the energy storage system will be analyzed in addition to developing a workflow for defining optimal location of the energy storage system to have maximum impact on system inertia. Further, the economic viability and benefits of deploying the designed control algorithms in existing and new plant deployments will be assessed. The proposed method provides the following features: breaks from rigid virtual synchronous machine by extending the physics-based analogy to a virtual line-shaft of adjustable number of masses and providing high level of virtual damping. Flexible control approach can be optimally tuned to help damp oscillations, resilient and robust in both grid-tied and islanded conditions.

EPRI 137937 **Smart Inverter Setting Guidance**

The latest IEEE 1547-2018 outlines a variety of smart inverter functions (Volt-var, Volt-watt, Watt-var, Fixed power factor, etc.) that are to be available in all distributed energy resources (DER). In California and Hawaii, where penetration levels of PV are relatively high and growing, interconnection practices have already been updated in recent years to require inverters to have similar capabilities. Since New York has very few systems deployed with these functions, many NY utility personnel responsible for interconnection requirements are trying to determine what smart inverter functions to enable and which settings to apply to meet the needs of specific applications of grid connected DER. This project will provide comprehensive guidance and methodological analyses for selecting smart inverter functions and settings in the State of New York. The project will focus on the key factors when considering smart inverter autonomous settings, reviewing and comparing the latest industry standards for settings, and providing a systematic approach to determine settings for both new and common inverter functions.

Tagup 137939 **Machine Learning Platform for Ratio Transformer Failure Predictions**

Transformer failures are estimated to cost $23B per year in property damage and equipment breakdown which lead to high insurance premiums, inspection and maintenance costs. Large power transformers have online monitoring systems to pre-empt failures, but these systems are not economical for transformers found on distribution networks where analytics are limited. National Grid operates 1,300 3-phase, clustered/platform mounted ratio transformers in NY. These ratio transformers step-up or step-down voltages from legacy voltages to the current voltage constructions standards. They represent potential single points of failure for a circuit, and so can cause expansive and expensive power outages when they fail. The opportunity exists to improve a customer's service reliability while also reducing rates. Tagup, Inc. shall work with National Grid to develop and deploy advanced failure prediction analytics on National Grid's fleet of ratio transformers. This Statement of Work (SOW) consists of three (3) NYSERDA project categories completed in four (4) distinct phases. Overall project objectives are to confirm an adequate technology fit (Phase I), build critical product and analytics capabilities (Phase II), and validate deployed analytics at scale (Phase III & IV).

NYPA 137943 **Optimal Forecasting Solution for Overhead Line Operations**

According to a 2017 NYISO quarterly report, the day-ahead congestion revenue totaled $104 million in 2017-Q3. These bottlenecks often prevent conventional and green energy from northern upstate resources to downstate, southern loads. Some new transmission line projects, for example NAT/NYPA proposal T025, are being planned to address these congestion problems. However, these transmission projects normally have long durations. To solve the problem, some pilot projects based on various real-time Dynamic Line Rating (DLR) technologies have been experimented. However, due to the nature of the small overhead conductor thermal time constant, the traditional real-time DLR is rarely used by operators to deal with congestion problems. Alternatively, a latest combined U.S. Department of Energy (DOE) funded forecast hour-ahead/day-ahead /real-time line ratings solution, can be easily implemented by utility companies, rather than the existing real-time DLR method to address congestion problems. The congestion problem is directly related to the line power transfer capacity/rating primarily constrained by its thermal limits. Currently most power delivery system planners and grid operators still utilize traditional Static Line Ratings (SLRs) based on a fixed set of conservative environmental conditions to establish a limit on the amount of current a line can safely carry without overheating. According to a 2014 DOE report titled "Dynamic Line Rating Systems for Transmission Lines", some utilities observed real-time capacities increase of 30%-44% above the SLRs. Extra capacity within existing transmission line is not utilized by operators due to the nature of the small overhead conductor thermal time constant which means the real-time line ratings can vary quickly. Some line rating technologies based on optimized forecast/real-time weather data have been developed. The project will demonstrate a WindSim Computational Fluid Dynamics (CFD)-enhanced forecast/real-time transmission line rating system, called WindSim Power Line Optimization Solution (WPLS), that provides more stable line ratings and helps enhance the capacity of existing transmission infrastructure. The goal of the project is to demonstrate WPLS can effectively address the bottleneck challenges faced by the Contractor and other New York State utilities.

EPRI 137944 — **Control System Forensic Capability Study**

The Electric Power Research Institute, Consolidated Edison, Inc., The MITRE Corporation and General Electric (GE) Grid Solutions shall conduct a research study on the discovery and identification of forensic artifacts within Industrial Control System (ICS) equipment. The Team will work with intelligent electronic devices from General Electric (GE) who will serve as the industry partner for the project. The Contractor's Cyber Security Research Lab will be utilized for the testing and analysis. MITRE Corporation will participate in testing, serving as the Red Team which will conduct attacks upon the testbed equipment. The goal is to identify technical tools capable of forensic artifact collection, development of processes for forensic artifact collection, and documentation of available forensic artifacts for ICS equipment within the scope of the project. Additionally, the first prototype of a forensic harvester tool will be developed to accomplish the collection of artifacts based upon the scope of the equipment and the attacks that are tested.

EPRI 137947 — **Learning Smart Inverter Study**

As part of the New York Reforming the Energy Vision initiative (REV), New York State is seeking to improve the strength of New York State's grid, as well as increase the supply of electricity from renewable energy sources. To accomplish this, the distribution system will need to be able to accommodate a large amount of Distributed Energy Resources (DER) on the distribution system. Smart inverters can help accomplish these goals, but the increased complexity caused by settings choices poses a considerable barrier. Additionally, as the distribution system becomes increasingly reliant on generation provided from inverters, response during faults or other emergency conditions will be important to maintain grid stability. Learning inverters may have the ability to improve their ride-through capabilities or adjust anti-islanding methods for a more stable grid. As DER integration continues to rise in New York State and throughout the country, it is important that DER act as both a generation and grid stability resource. Previous research by Electric Power Research Institute and Rensselaer Polytechnic Institute have shown that grid impedance from the inverter to the source can be estimated by active control of the inverter. Analysis of cloud induced power and voltage variability suggests it may be possible to estimate the grid impedance passively as well. The objective of this research is to study the ability for an inverter to learn grid parameters, such as impedance (X, R, and X/R ratio), timing and magnitude of steady-state low or high voltages and voltage signature during fault conditions. In addition to understanding these parameters, the Project will seek to apply these learnings to inverter reactive power applications.

NYPA 137952 — **Advanced Solar and Load Forecasting (Phase 3)**

Solar power forecasting plays a critical role in the operation of an Independent System Operator and utility. Accurate forecasts help maintain grid reliability, optimize production of renewables, and reduce operating costs. Of particular interest to the ISO's and utilities are sudden changes in solar irradiance, termed "ramp events", due to the movement of clouds. One significant impact of ramp events to the grid is on ancillary service requirements, necessary to manage such variability. Ramp events can also cause voltage fluctuations in the distribution grids and trigger actions of automated line equipment (e.g. tap changers), leading to additional maintenance costs. In high penetration solar regions, forecasts must be made for both transmission and distribution connected resources – either behind the meter or on the distribution system. Particularly for distributed solar resources, forecasting can be a challenge due to the lack of visibility of the resource. The project will use a combination of advanced technologies to improve solar and load forecasting for utility operations. Cost-effective HD sky imagers will be deployed while leveraging other advanced sources of data to improve now-casting (current time to tens of minutes ahead). This project extends previous concepts by deploying a network of imagers covering both centralized and distributed PV. Algorithms and software will be developed to stitch together and assimilate a regional solar forecast from the imager data.

Clarkson University 148516 — **Real-Time Interconnection Studies and Control of New York Offshore Wind**

As a part of the plan to have 70 percent of electric generation from renewable energy by 2030 and 100 percent of carbon-free electricity power by 2040, New York State has set the nation-leading goal in offshore wind development of 9 GW by 2035. Interconnecting shore power to land poses many challenges to the New York State Power System (NYSPS). The challenges mainly arise from fault conditions and contingencies. To provide interconnection assessment and solutions for offshore wind energy, the objectives of this project are: 1) Real-time modeling of 9 GW wind energy system and its interconnection with NYSPS and 2) Real-time system impact studies of faults, transient stability, and fault ride through with offshore wind.

Using NYS Mesonet Data For ISM-Based Renewable, Load, and Outage Forecasts

Electrical Distribution Design (EDD) will team with UAlbany and two utility partners, Orange and Rockland Utility (ORU) and Central Hudson Gas & Electric (CHGE), to develop a product that combines the New York State (NYS) Mesonet with Integrated System Models (ISMs) to improve real-time situational awareness for electric load variations, renewable generation variations, and storm outages. This project will leverage the NYS Mesonet, ISMs, and outage prediction to produce a product that seamlessly integrates weather-dependent load forecasting, renewable generation forecasting, and storm outage forecasting, with an expansion of the NYS Mesonet that includes high speed measurements at large solar generation sites.

Project Synopsis – Grid Modernization Lab Consortium (GMLC) - National Labs

ACRONYM	FULL NAME	LOCATION
ANL	Argonne National Laboratory	Argonne, IL
BNL	Brookhaven National Laboratory	Upton, NY
LBNL	Lawrence Berkeley National Laboratory	Berkeley, CA
LLNL	Lawrence Livermore National Laboratory	Livermore, CA
NREL	National Renewable Energy Laboratory	Golden, CO
PNNL	Pacific Northwest National Laboratory	Richland, WA
SNL	Sandia National Laboratory	Albuquerque, NM
LANL	Los Alamos National Laboratory	Los Alamos, NM
SLAC	SLAC National Accelerator Laboratory	Menlo Park, CA
INL	Idaho National Laboratory	Idaho Falls, ID
SRNL	Savannah River National Laboratory	Aiken, SC
ORNL	Oak Ridge National Laboratory	Oak Ridge, TN
NETL	National Energy Technology Laboratory	Pittsburgh, PA
NBL	New Brunswick Laboratory	Argonne, IL

PROJECT NAME	DESCRIPTION	LABS	PARTNERS	FUNDING
Project 1: Foundational Analysis for GMLC Establishment/Analysis	Develop an integrated suite of grid modernization metrics that leverage current industry practice, emerging industry additions (e.g. extreme event metrics from NERC) and develop new metrics that reflect emerging grid attributes and architectures. Conduct baseline modernization assessments and provide ongoing dashboard for policy makers, regulators and industry stakeholders.	ANL, BNL, LBNL, ORNL, NREL, PNNL, SNL, LLNL, and LANL	North American Electric Reliability Corporation (NERC), National Association of Regulatory Utility Commissioners (NARUC), EIA	$4.75M proposed over three years
Project 2: Grid Architecture	Build a new stakeholder-driven architecture for grid modernization, provide it to the industry along with the tools they need to adapt it to their needs, and use it to inform the playbook for GMLC program managers.	PNNL, ANL, NREL, ORNL, LANL, LBNL, LLNL, SNL	GE-Alstom, Electric Power Research Institute (EPRI), GWU, United Technologies (UTC), Smart Grid Interoperability Panel (SGIP), Omnetric Group, California ISO	$1M+ proposed over three years
Project 3: Interoperability	This project provides strategic vision for interoperability endorsed by stakeholders with tools to measure interoperability maturity and the progress of related investments. It prioritizes interoperability gaps and develops an overarching roadmap for stakeholder endorsement.	PNNL, NREL, ANL, LBNL, SNL	SGIP, National Institute of Standards and Technology (NIST), GridWise Architecture Council (GWAC), EPRI, Standards Developing Organizations (SDOs), Utilities, Vendors	$1M+ proposed over three years
Project 4: Grid Modernization Laboratory Consortium Testing Network	Establish a Grid Modernization Laboratory Consortium - Testing Network (GMLC-TN); federated lab-based resource for standards-based testing and validation of grid devices and systems. Develop and establish a Grid Modernization Laboratory Consortium - Open Library (GMLC-OL) public repository for validated component models, simulation tools and testing resources.	SNL NREL, PNNL, ORNL, ANL, INL, LBNL, SRNL, BNL, LLNL	SGIP, NIST, GWAC, EPRI, Universities, Utilities, Vendors	$1M+ proposed over three years
Project 5: Grid Services and Technologies Valuation Framework	Develop a widely accepted, well-tested valuation methodological framework for evaluating the collection of value streams (net benefits) that can be provided by different grid-related technologies and services.	ORNL, PNNL, NREL, LBNL, ANL, SNL, LANL	TVA, Eastern Interconnection Planning Collaborative, NARUC/Eastern Interconnection States Planning Council	$3M proposed over three years
Project 6: Grid Sensing and Measurement Strategy	Identify measurement requirements along with associated data management and communication systems to enable full visibility of grid system state. This methodology will include defining the grid state, developing a roadmap along with a framework to determine sensor allocation for optimal results.	ORNL, PNNL, NETL, LLNL, ANL, NREL, SNL, LBNL, LANL	EPRI, Southern Co, Electric Power Board of Chattanooga (EPB), Entergy, OSIsoft, Dominion, TVA, ComEd, North American SynchroPhasor Initiative (NASPI)	$1M+ proposed over three years

Pioneer Regional Partnerships

PROJECT NAME	DESCRIPTION	LABS	PARTNERS	FUNDING
Project 7: Southeast Consortium	Identify measurement requirements along with associated data management and communication systems to enable full visibility of grid system state. This methodology will include defining the grid state, developing a roadmap along with a framework to determine sensor allocation for optimal results.	ORNL, SRNL	University of Tennessee, EPB, Southern Company, TVA, UNC-Charlotte, Duke Energy, Santee Cooper, Clemson	$1M proposed over two years
Project 8: Industrial Microgrid Analysis and Design for Energy Security and Resiliency	Investigation, development, and analysis of the risks, costs, and benefits of a microgrid utilizing renewable energy systems at the UPS WorldPort and Centennial Hub facilities. Develop a roadmap to help industries evaluate microgrid adoption by defining institutional and regulatory challenges associated with development of industrial-based resilient systems.	ORNL, SNL	United Parcel Service, Waste Management, Bums McDonnell, Harshaw Trane, LG&E, State of Kentucky	$1M proposed over two years
Project 9: DER Siting and Optimization Tool for California	Deliver to stakeholders an integrated distributed resource planning and optimization platform, hosted online, able to identify meaningful behind-the-meter DER adoption patterns, potential microgrid sites and demand-side resources, and evaluate the impacts of high renewable penetration feeders on the distribution and transmission grid.	ANL, BNL, LBNL, LLNL, NREL, SLAC	California PUC, Pacific Gas and Electric (PG&E), Southern California Edison (SCE), Metropolitan Council of Governments, New York State Energy Research and Development Authority (NYSERDA)	$1.3M proposed over two years
Project 10: Smart Reconfiguration of Idaho Falls Network	Improve physical security of the Idaho Falls distribution system by testing smart reconfiguration, intelligent DR utilizing loads as a resource, controlled islanding, black start procedures for emergency service, and resynchronization in the presence of DERs.	PNNL, INL	Idaho Falls Power, Schweitzer Engineering Labs, Washington State University, Utah Associated Municipal Power Systems	$1M proposed over two years
Project 11: Vermont Regional Partnership Enabling the Use of DER	Assist Vermont utilities in meeting the state's ambitious goal of obtaining 90% of its energy from renewable sources by 2050 through (1) DER integration, (2) DER control, (3) validation of	SNL, NREL,	Green Mountain Power, Vermont Electric Cooperative, Vermont Electric Company, University of Vermont	$1M proposed over two years

PROJECT NAME	DESCRIPTION	LABS	PARTNERS	FUNDING
	wind and solar forecasting, and (4) techno-economic analysis of energy storage.			
Project 12: Grid Analysis and Design for Resiliency in New Orleans	Conduct technical evaluations to assess energy and critical infrastructure vulnerabilities, and to identify cost effective options to improve the resiliency of both the electrical grid infrastructure and the community.	SNL, LANL	City of New Orleans, Rockefeller Institute, Entergy, US Army Corps of Engineers	$1M proposed over two years
Project 13: Alaska Microgrid Partnership	Develop a design basis framework and programmatic approach to assist stakeholders in their efforts to reduce diesel fuel consumption by at least 50% in Alaska's remote microgrids without increasing system lifecycle costs, while improving overall system reliability, security, and resilience.	NREL, PNNL, LBNL, SNL	Alaska Energy Authority, University of Alaska-Fairbanks, University of Alaska- Anchorage, Renewable Energy Alaska Project, Intelligent Energy Systems	$1M proposed over two years
Project 14: Technical Support to the New York State REV Initiative	Provide objective Technical Assistance by a team of National Lab experts to NYS agencies and policy makers on significant policy issues including retail market design, rate design, customer engagement, utility planning/operations, DER integration, cyber security.	BNL, LBNL, PNNL, INL	NYSERDA, NY State Smart Grid Consortium, Modern Grid Solutions, ICF International, Regulatory Assistance Project	$1M proposed over two years
Project 15: Grid Frequency Support from Distributed Inverter-Based Resources in Hawaii	Develop, simulate, validate, and deploy practical solutions in Hawaii that enable distributed energy resources (DERs) to help mitigate bulk system frequency contingency events on the fastest time scale (milliseconds to seconds). Validate the ability of real hardware inverters to support grid frequency in an environment that emulates the dynamics of a HECO power system.	NREL, SNL	Hawaiian Electric Companies, Enphase Energy, Fronius USA, Forum on Inverter Grid Integration issues, Energy Excelerator	$1M proposed over two years
Project 16: Midwest Interconnection Seams Study	Convene industry and academic experts in power systems to evaluate the HVDC and AC transmission seams between the U.S. interconnections and propose upgrades to existing facilities that reduce the cost of modernizing the nation's power system.	NREL, PNNL, ANL, ORNL	Iowa State University, Southwest Power Pool (SPP), Midcontinent Independent System Operator (MISO), Western Area Power Administration (WAPA), Solar Energy Industries Association (SEIA),	$1.2M proposed over two years

PROJECT NAME	DESCRIPTION	LABS	PARTNERS	FUNDING
			Minnesota Power, Xcel Energy, Tetra Tech, Transgrid Solutions, Utility Variable-Generation Integration Group (UVIG), and Bryndan Associates	
Project 17: Transactive Campus Demonstration	Three campuses (PNNL, UW and WSU) will develop and test a range of transactive control activities on each of the 3 campuses. They will also develop the ability to coordinate across these three campuses to provide coordinated services to the PNW power system and their serving distribution utilities based upon the transactive response of key loads on the campuses. The UW will emphasize energy storage and coordination for peak management and provision of flexibility. The WSU campus will leverage its microgrid and major campus loads and thermal storage to deliver transactive response. And PNNL will advance controls in its new SEB grid building and other campus loads to help the City of Richland better manage its demand limits. OE and BTO collaborated in the design and cost share of the project.	PNNL	Washington State Clean Energy Fund, University of Washington, Washington State University	$2M DOE, $2M WA CEF over 18 months

Crosscutting Activities

PROJECT NAME	DESCRIPTION	LABS	PARTNERS	FUNDING
Project 17: Standards and Test Procedures for Interconnection and Interoperability	This project will build on prior efforts and leverage existing activities spanning multiple DOE programs that are developing interconnection and interoperability standards and test procedures to: • harmonize requirements across jurisdictions • eliminate conflicting requirements across technology domains • streamline conformance test procedures to the fullest extent possible	NREL, PNNL, LBNL, SNL, ANL, ORNL, INL	SGIP, NIST, GWAC, EPRI, Standards Organizations, Utilties, Vendors Solutions, UVIG, and Bryndan Associates	$3.5M

PROJECT NAME	DESCRIPTION	LABS	PARTNERS	FUNDING
Project 18: Definitions, Standards and Test Procedures for Grid Services	Enable and spur the deployment of a broad range of distributed energy resource (DER) devices by defining a test protocol to characterize their ability to respond to grid signals and define a standard set of grid services and "drive cycles" to describe the capabilities that DERs must have to provide them.	PNNL, NREL, ORNL, SNL, LBNL, ANL, INL, LLNL	Independent Test Labs, EPRI, Standards Organizations, Utilities, Vendors	$6.5M over three years
Project 19: Advanced Sensor Development	Increase visibility throughout the energy system including transmission, distribution, and end-use by developing low-cost, accurate sensors. Additionally, next generation asset monitoring devices will help determine state of grid components prior to failure.	ORNL, PNNL, NETL, NREL, SNL, LBNL	EPRI, University of Tennessee, Southern Co, EPB, Entergy, Eaton, SmartSense, National Instruments, Dominion, TVA, CommEd, NASPI	$6M over three years
Project 20: Integrated Multi Scale Data Analytics and Machine Learning for the Grid	Develop a low cost scalable infrastructure for integrating disparate high fidelity data sources. Machine learning methodologies will be used to assist in transforming data into actionable intelligence. This platform will allow multiple entities to collaborate on data utilization.	LANL, SNL, LBNL, ORNL, NREL, ANL	OSIsoft, National Instruments	$2.5M over three years
Project 21: Control Theory	Develop new control solutions including topologies, algorithms, and deployment strategies for transitioning the power grid to a state where a huge number of distributed energy resources are participating in grid control to enable the grid to operate with lean reserve margins. The theory effort will recognize the need to engage legacy control concepts and systems as we transition to more distributed control.	LANL, PNNL, ANL, INL, NREL, SNL, LLNL	Oncor, PJM Interconnection, United Technologies Research Center	$6.5M over three years
Project 22: Multi-Scale Integration of Control Systems (EMS/DMS/BMS)	Create an integrated grid management framework for the end-to-end power delivery system - from central and distributed energy resources at bulk power systems and distribution systems, to local control systems for energy networks, including building management systems.	ANL, BNL, LANL, LLNL, NREL, PNNL, SNL	Alstom Grid, Duke Energy, PJM	$3.5M over three years
Project 23: Development of Integrated Transmission,	Build on best-in-class Lab capabilities to develop an integrated, flexible, open source framework for coupling TDC models and simulations. Validate	PNNL, LLNL, NREL, ANL, ORNL, SNL,	SCE, National Grid, PJM, Peak Reliability, NRECA,	$4M over three years

PROJECT NAME	DESCRIPTION	LABS	PARTNERS	FUNDING
Distribution, and Communication (TDC) Models	framework and models on hardware testbed. Demos with partners will include distributed /wide area controls and DER.	INL	CAISO, NYISO, ERCOT	
Project 24: Extreme Event Modeling	Improve preparation, planning, and response to extreme events such as hurricanes, EMP, etc. Focus on developing analysis prototype demonstrating up to 500x performance improvements in modeling cascading events and probabilistic N-k contingency analysis.	LANL, PNNL, LLNL, ANL, BNL, NREL, ORNL, SNL	PJM, Dominion, Electric Reliability Council of Texas (ERCOT), NERC, FERC, IEEE Cascading Failure Working Group, University of Tennessee-Knoxville Center for Ultra-Wide-Area Resilient Electric Energy Transmission Networks (UTK-CURENT)	$3M over three years
Project 25: Computational Science for Grid Management	Address increasing computational complexity and reduced time-to-solution requirements for grid planning and operations via new scalable solvers, dynamics, and uncertainty analysis. Builds upon existing DOE-funded work (GridPack, M2ACS Program, PETSc and SUNDIALS libraries).	ANL, PNNL, NREL, SNL, LLNL, LANL	PJM, ISO-New England	$1.5M over three years
Project 26: Threat Detection and Response with Data Analytics	Develop technologies and methodologies to protect the grid from advanced cyber and all-hazard threats through the collection of disparate data and the employment of advanced analytics for threat detection and response.	INL, LBNL, LLNL, ORNML, PNNL, SNL	Electric Power Board (EPB), National Rural Electric Cooperative Association (NRECA)	$3M over three years
Project 27: Distribution System Decision Support Tools	Project will develop tools, identify gaps and provide technical assistance/training targeted at state regulators and small/medium utilities (e.g., co-ops and municipal utilities) on advanced distribution system planning for a modernized grid that incorporates high levels of DER.	NREL, LBNL, PNNL	American Public Power Association (APPA), National Rural Electric Cooperative Association (NRECA), Interstate Renewable Energy Council, Pedernales Electric	$2.5M over three years

PROJECT NAME	DESCRIPTION	LABS	PARTNERS	FUNDING
			Cooperative, National Grid, Arizona Public Service Company, Black and Veatch	
Project 28: Development and Deployment of Multi-Scale Production Cost Models	Develop ability to more accurately estimate economic impact of renewables, storage, and other technologies. Research scalable methods for deterministic and stochastic PCM, higher resolution grid models, applications of uncertainty quantification and high performance computing (HPC). New capabilities will be deployed with system planners through PCM workshops.	NREL, SNL, ANL, PNNL, LLNL	MISO, Energy Exemplar, PJM Interconnect, NRECA	$3M over three years
Project 29: Future Electric Utility Regulation	Provide technical assistance and policy analysis to state PUCs considering incremental and fundamental changes to electric utility regulation; enhance utility financial analysis modeling tools focused on ratemaking and regulatory issues that arise with increased penetration of DER.	LBNL, NREL, PNNL, SNL, LANL, NETL	National Association of Regulatory Utility Commissioners	$3M over three years
Project 1: Virtual Batteries	Develop a characterization methodology to quantify the capacity/availability of virtual storage resources through transactive control of building loads to deliver grid and other transactive services. This work will be conducted in coordination with OE, ARPA-E, and PNNL's Control of Complex Systems Initiative (PNNL LDRD funded).	PNNL	University of Florida, TVA, BPA, and (potentially) UTRC.	$3.6M over three years
Project 2: Message Bus	Volttron Extension that provides building level data standardization to enable transactive services from connected equipment and buildings.	SLAC		$0.9M over three years
Project 3: Economic Dispatch	Design, develop, and field a multi-purpose transactive controller and associated open source algorithms that will ensure real time optimal operation of building equipment, increase electric grid reliability, and lead to the goal of clean, efficient, reliable and affordable next generation buildings and energy systems.	PNNL		$3M over three years
Project 4: Transformer	Develop and evaluated transactive load control strategies for distribution and	SRNL	DOD, Clemson, Duke Power,	$4.5M over three

PROJECT NAME	DESCRIPTION	LABS	PARTNERS	FUNDING
Efficiency	building level transformers that improve the efficiency of integrated electric energy system and extend the service life of utility and building assets. This work will be conducted in coordination with the DOE Appliance Standards Program.		SCE&G, Santee Cooper	years
Project 5: Hybrid Inverter	Develop universal transactive driver interface for the Volttron platform to enable near real-time control of DER-based, community scaled power electric.	ORNL		$1.5M over three years
Project 6: Connected Loads	Develop whole-building transactive, supervisory load control and fault detection and diagnostics for improving the energy efficiency, reducing peak demand, and enabling grid responsive loads.	ORNL	Southern Company, Emerson Climate Technologies	$3M over three years

Fuel Cells Technologies Office

PROJECT NAME	DESCRIPTION	LABS	PARTNERS	FUNDING
Project 1: Optimal Stationary Fuel Cell Integration and Control	This project has two main objectives: 1) to implement an open-source dispatch and load control tool for building management that can communicate and transact with a fuel cell integrated building system and the grid for optimized dispatch of building components, and 2) to implement a planning tool for optimal component selection and sizing based on optimal resource control for distributed energy systems and smart building component using location specific energy markets, building energy modeling, and chosen dispatch control strategy.	NREL, PNNL	Washington State University, Doosan Fuel Cell America, Inc., Plug Power, IN.c, Humboldt University, Ballard	$2.1M proposed over three years
Project 2: Integrated Systems Modeling of the Interactions between Stationary Hydrogen, Vehicle, and Grid Resources	The goal of this project is to establish the available capacity, value, and impacts of interconnecting hydrogen infrastructure and fuel cell electric vehicles to the electric grid. The first objective is to quantify the opportunity of utilizing flexibility from hydrogen systems to support the grid. The second objective is to develop and implement methods to assess optimal system configuration and operating strategy for grid-integrated hydrogen systems. Data products (e.g.,	LBNL, NREL, INL		$1.65M proposed over three years

PROJECT NAME	DESCRIPTION	LABS	PARTNERS	FUNDING
	equipment costs, market data, vehicle operation and fueling data) will be available for release to help establish a benchmark for future work.			

Solar Energy Technologies Office

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Project 1: Additively Manufactured Photovoltaic Inverter (AMPVI)	In this three-year integrated project, activities will be focused on development and validation of the foundational building blocks needed for the additively manufactured photovoltaic inverter (AMPVI). Technology development include high voltage SiC-based power block, gate driver, controller board, and control algorithms, magnetic design tools, additive manufacturing inverter design, prototyping, and integration testing.	NREL, ORNL	Purdue University	$4.5M proposed over three years
Project 2: Combined PV/Battery Grid Integration with High Frequency Magnetics Enabled Power Electronics	Advanced DC-DC and DC-AC converter-based integrated modules and associated systems architectures and topologies will be developed for 13.8kV, 60Hz direct grid connection using SiC devices. In parallel, advanced magnetic cores and high frequency (HF) transformers built upon them will be developed to enable DC-DC and DC-AC converters with energy storage (ES) that serve as the building blocks for the proposed technologies. System architecture studies informed by market driven technical requirements will also be performed to provide guidance for the on-going R&D activities throughout.	NETL	NC State University, Eaton, Carnegie Mellon University, NASA	$4M proposed over three years
Project 3: Solar Resource Calibration, Measurement, and Dissemination	Develop and disseminate accurate solar resource information through improvement in instrumentation, traceable ISO-17025 accredited calibration and characterization, and resource modeling. Develop industry relevant consensus standards and best practices to lower barriers and reduces financing risk and costs.	NREL		$2.5M proposed over three years
Project 4: Improvement and Validation of the	Strengthen and increase relevance of the System Advisor Model (SAM) as	NREL		$2.2M proposed

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
System Advisor Model (SAM)	the best-in-class modeling software for techno-economic analysis of solar energy technologies. Research and implement cutting-edge system performance and financial models. Develop open platforms to enable custom, proprietary, and high value-add extension plugins. Technical support, documentation, and training to promote stakeholder engagement. Integrate the latest and most accurate databases for components, solar resource, tariffs, and costs.			over three years
Project 5: Dynamic Building Load Control to Facilitate High Penetration of Solar Photovoltaic Generation	Responsive loads that can be controlled temporally and spatially to minimize difference between demand and PV production to minimize voltage variation and reduce two-way power flow. Develop models and perform system-level simulation; Model-based control design to generate control software; Controller and communication network development; Unit-level and system-level testing; Field Testing	ORNL	Southern Company, University of Tennessee, Georgia Tech	$3M proposed over three years
Project 6: Concentrating Solar Power in a SunShot Future	Analyze the role of dispatchable concentrating solar power (CSP) in providing multiple grid services to increase the overall penetration of solar energy and mitigate the variability impacts of solar PV. Using industry vetted tools and methods simulate the value of CSP with TES providing multiple grid services over all time scales of interest	NREL	GE	$2.1M proposed over three years
Project 7: Secure, Scalable, Stable Control and Communication for Distributed PV	The goal of this effort is to develop a distributed control and communications architecture that refines the SunShot Systems Integration communications target metrics by clearly articulating the impact of each metric on the grid. Depending on the application, some metrics may be relaxed significantly, resulting in significant cost savings. For other applications, the metrics may not be sufficient to maintain or improve the stability and security of the power grid with very high penetrations of PV generation (e.g., 2030).	SNL	Montana Tech University	$2.7M proposed over three years
Project 8: Opportunistic	The objective of the proposed	NREL		$2.7M

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Hybrid Communications Systems for Distributed PV Coordination	research is a full-scale, operational implementation of the opportunistic hybrid communication system. The system is considered hybrid because it utilizes different communications pathways, such as SCADA systems, satellite communications, and powerline communications. It is opportunistic in that it chooses to route messages through each of these systems based on recent data about latency and availability to ensure reliable message passing. From a PV perspective, the research will allow the current gaps in knowledge on grid performance, phrased in terms of reliability, scalability, interoperability, flexibility, and security, to be filled with measured data from PV systems and other monitoring points in the power system and with robust inferences from state estimation algorithms.			proposed over three years
Project 9: Accelerating Systems Integration Codes and Standards (ASICS)	This project updates the codes and standards identified under the grid performance and reliability topic area focusing on the distribution grid. The standards addressed are the IEEE 1547 series, UL 1741 and the NEC. Establishing accelerated development of new interconnection and interoperability requirements and conformance procedures is the key result for this project.	NREL, SNL		$3M proposed over three years
Project 10: Frequency Response Assessment and Improvement of Three Major North American Interconnections due to high penetrations of Photovoltaic Generation	Directly addressing the reduced system inertia and frequency response challenge under high (60-90%) solar penetration for all three major grids (WECC, ERCOT, and EI). Technical Approach: 1) Dynamic simulations using power grid models and best-estimated high PV penetration scenarios, 2) Develop grid-support inverter control.	ORNL, NREL	University of Tennessee, GE, NREL	$2.2M proposed over three years
Project 11: Rapid QSTS Simulations for High-Resolution Comprehensive Assessment of Distributed PV Impacts	Goal: Development new and innovative methods for rapid QSTS Simulations to assess Distributed PV impacts accurately. Objective 1: Reduce the computational time and complexity of QSTS analysis to achieve year-long time series solutions that can be run in less than	SNL, NREL	Georgia Tech, University of Pittsburgh, EPRI, CYME	$4M proposed over three years

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
	5 minutes at a time step of 1 second. Objective 2: Develop high-resolution proxy data sets that will be statistically representative of existing measured load and PV plant data and will provide an accurate representation of PV impacts. Objective 3: Improve both the time and accuracy of QSTS analysis in order to make it the industry-preferred PV impact assessment method.			
Project 12: CyDER: A Cyber Physical Co-simulation Platform for Distributed Energy Resources in Smart Grids	Innovations: a) discrete-event co-simulation platform b) QSTS: Quasi-Static Time Series Co-simulation c) Real-time Data Acquisition for Predictive Analytics, d) FMI: Functional Mockup Interface, e) Ptolemey II: Cyberphysical simulation framework	LBNL, LLNL	SunEdison, ChargePoint	$4M proposed over three years
Project 13: An Integrated Tool for Improving Grid Performance and Reliability of Combined Transmission-Distribution with High Solar Penetration	To develop a software tool suite, comprising of three tools, for improving grid reliability and performance of combined transmission-distribution systems under high solar penetration, a) High-fidelity combined transmission-distribution steady-state analysis tool, b) Simultaneous transmission (T) and distribution system (D) dynamic and protection system analysis tool, and c) Distribution system state estimation (DSSE) with AMI, PMU, new sensors, and asynchronous updates.	ANL, RNEL	Illinois Institute of Technology (IIT), Electrocon International Inc., and McCoy Energy	$2.8M proposed over three years
Project 14: Enabling a High penetration of Distributed PV Through the Optimization of Sub-Transmission Voltage Regulation	Voltage regulation challenges at sub-transmission will be a barrier for high penetration of photovoltaics (PVs). We will develop a Coordinated Real-time Sub-Transmission Volt-Var Control Tool (CReST-VCT) to optimize the use of reactive power control devices to stabilize voltage fluctuations caused by intermittent PV. We will couple this tool to an Optimal Future Sub-Transmission Volt-Var Planning Tool (OFuST-VPT) for short- and long-term planning. Together, the real-time control and planning tools will remove a major roadblock to the increased use of distributed PV.	PNNL	NC State University, GE, One-Cycle Control, Duke Energy	$3M proposed over three years

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
	CReST-VCT will be demonstrated and validated on North Carolina State University (NCSU) microgrid test systems with hardware-in-the-loop simulations. Field demonstration will be performed on the Duke Energy system feeder test bed and selected sub-transmission buses.			
Project 15: Visualization and Analytics of Distribution Systems with Deep Penetration of Distributed Energy Resources (VADER)	Objective: Understand the impact of technologies on the distribution system and how they can be used for planning and operations to increase PV penetration (reduce interconnection study costs and approval duration). Approach: Build a set of open source tools. Verify tools utilizing data from industry and utility partners. Validate the platform in a pilot testbed with HIL and data from deployed hardware in the field.	SLAC	Stanford, Opal-RT, Charge Point, SunPower, City of Palo Alto Utilities, Technical Advisory Group	$4M proposed over three years
Project 16: Stabilizing the Power System in 2035 and Beyond: Evolving from Grid-Following to Grid-Forming Distributed Inverter Controllers	The aim of the proposed project is to develop distributed inverter controllers which provide a low-resistance path from the current inertia-dominated grid paradigm to a future grid paradigm dominated by low-inertia power systems with 100's of GWs of PV integration.	NREL	UC Santa Barbara, University of Minnesota, Arduino, SunPower, HECO, Schneider	$3.8M proposed over three years

Vehicle Technologies Office

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Project 1: Vehicle to Building Integration Pathway	The Vehicle to Building Integration Pathway project will develop and demonstrate pre-normative methods needed to develop a standardized and interoperable communication pathway and control system architecture between Plug-in Electric Vehicles (PEVs), Electric Vehicle Support Equipment (EVSE) and Building/Campus Energy Management Systems (BEMSs) to enable the integration of clean variable renewable sources with workplace PEV charging infrastructure to promote greater PEV adoption. This communications and control platform will provide access to real-time system	ANL, INL, LBNL, NREL, PNNL	AeroVironment, Bonneville Power Administration, University of Delaware, DTE Energy	$3.4M over three years

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
	monitoring information, establish an infrastructure to coordinate intelligent assets, manage energy consumption behind the meter, reduce peak demand charges resulting from vehicle charging, and potentially participate in energy and/or ancillary services markets.			
Project 2: Systems Research Supporting Standards and Interoperability	The objective of the proposed project is to address the considerable uncertainty regarding the degree to which PEVs can provide grid services and mutually benefit the electric utilities, PEV owners, and auto manufacturers. How can the potential benefits be unlocked without negative unintended consequences? This project will answer this question by leveraging capabilities of multiple national laboratories with vehicle/grid integration (VGI) to perform hardware-in-the-loop (HIL) studies that integrate communication and control system hardware with simulation and analysis activities.	ANL, INL, LBNL, NREL, ORNL, PNNL	Bonneville Power Administration, DTE Energy, Eversource, University of Delaware, Siemens, California Energy Commission, USDRIVE Grid Interaction Technical Team	$3.6M over three years
Project 3: Modeling and Control Software to Support V2G Integration	Determining the feasibility of VGI by quantifying the potential value, cost, complexity, and risks in different implementations of VGI. Allocating available value among stakeholders and determining pathways for electrification of transportation to enable beneficial grid services such as mitigating renewables intermittency.	ANL, INL, NREL, LBNL, ORNL, PNNL	Bonneville Power Administration, California Energy Commission	$2.8M over three years
Project 4: Diagnostic Security Modules for Electric Vehicles to Building Integration	The overall goal of this project is to develop a Diagnostic Security Module (DSM) framework for creating an end-to-end security architecture for the integration of modern Plug-in Electric Vehicle (PEV) with Electric Vehicle Supply Equipment (EVSE) and a BEMS.	INL, ANL, NREL, PNNL	University of Louisiana-Lafayette, ChargePoint, California Energy Commission	$1.65M over three years

Wind and Water Power Technologies Office

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Project 1: Market and Reliability Opportunities for Wind on the Bulk Power System	This project aims to create a modeling framework that will model timescales from decades to seconds to help analyze the impact of wind generation on the power system while considering realistic market design and strategies. This framework will provide the ability to model the impacts of wind on the economics and reliability of the grid in a realistic market environment. Most integration studies have focused on modeling the physical characteristics of the grid, but market inefficiencies can hinder access to the physical flexibility that is available, as noted in the Wind Vision Roadmap. The inability of previous studies to consider these market impacts on system operations are a significant shortcoming of previous work in wind integration. In this study, we propose a framework that considers the market impacts on revenue sufficiency and therefore resource adequacy and system reliability. Without the ability to represent realistic markets in future models and studies, system operators and regulators will not be able to integrate wind generation efficiently, creating a more difficult and costly transition to a modern electric power system.	ANL, NREL	FERC, EPRI	$2.4M proposed over three years
Project 2: WindView: An Open Platform for Wind Energy Forecast Visualization	This project aims at providing solutions to maintain situational awareness in the control room as more wind generation is integrated in power systems. The team proposes to develop an open visualization platform "WindView" that can simultaneously display wind forecast information with system power flows for the operators to better understand the operational aspects of the system as more wind energy is integrated. Industry-available and research-grade forecasting tools can be interfaced with WindView to display the wind energy forecasts through cognitive coarsened information representation, such as quantiles, bar graphs, and other representations identified by the industry partners. Through use of publicly-available map-based layout, such as Google Maps, the network information, such as power flows, generation dispatch, etc., will be displayed to avail the wide-area information. The design of WindView	ANL, NREL	Western Area Power Authority, University of Texas at Dallas, ERCOT, NYISO	$1.8M proposed over three years

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
	will be shaped by the most pressing needs of the industry through feedback and participation with industry partners.			
Project 3: Power System Reliable Integration Support to Achieve Large Amounts of Wind Power (PRISALA)	Policymakers and industry stakeholders do not have sufficient access to clear and unbiased information about the characteristics of variable generation. This results in the creation of artificial limits to wind energy deployment that hinder development of bulk power system standards and increase the cost of maintaining reliability. According to the DOE Wind Vision Roadmap, "There is an important role for stakeholders in helping to develop best practices in power system operation and design, as well as in designing both physical and institutional systems to support achieving the Wind Vision." In this project, we will address key parts of the role identified in the Wind Vision by engaging with policy makers, regulators, international groups and regional planning and reliability organizations (RP&ROs) to deliver timely and objective information about wind energy.	NREL	UVIG	$1.5M proposed over three years
Project 4: Providing Ramping Service with Wind to Enhance Power System Operational Flexibility	The aim of the proposed wind-friendly flexible ramping product is to transform a negative characteristic of wind power, specifically "ramping", into an advantageous one. Through efficient management of wind ramps, a significant contribution to the reduction of integration costs of wind power can be obtained while simultaneously allowing the optimization of wind power as a ramping product in the market. Main project initiatives are: (i) Development of a probabilistic wind power ramp forecasting method to characterize and forecast ramps from a utility-scale perspective; (ii) Analysis and synthesis of ramping products specific to the proposed test system(s), allowing guidelines and recommendations to be derived with respect to spatiotemporal impacts and other case-specific considerations; (iii) Design of flexible ramping products which can be implemented in a new market model to co-optimize energy, reserve and ramping.; (iv) Validate the benefits of incorporating wind ramp forecasts and improved management of wind power dispatch, and demonstrate	NREL	EPRI, University of Texas at Dallas, MISO, ERCOT	$1.5M proposed over three years

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
	potential economic and reliability benefits; (v) Continue to develop the "GridLAB-ISO" tool and integrate the proposed ramping product model into it; use "GridLAB-ISO" to simulate an actual ISO system, and (vi) Create awareness of the benefits of flexible ramping products for the enhanced integration of wind energy, sharing methodologies and lessons learned with industry.			
Project 5: Understanding the Role of Short-Term Energy Storage and Large Motor Loads for Active Power Controls by Wind Power	The goal of this effort is to develop and test coordinated controls of active power by wind generation, short term energy storage, and large industrial motor drives for providing various types of ancillary services to the grid and minimizing loading impacts and thereby reducing operation and maintenance costs (O&M) and subsequently the cost of energy (COE) generated by wind power. This work will utilize the $30M multi-year DOE investments and unique characteristics of NREL's existing NWTC test site including a combination of multi-MW utility scale wind turbine generators, variable-frequency motor drives (VFD), new 8 MW energy storage testing facility, 1 MW solar PV array, and 7 MVA Controllable Grid Interface (CGI). This combination of technologies allows for the optimization, testing and demonstration of various types of active power controls (APC) by wind power in coordination with other generation sources (including regenerative loads) and energy storage that allows enhancing or, in some cases, substituting the APC services by wind power and reducing impacts on wind turbine component life and thus increasing the availability and reliability of the power supply from wind.	INL, NREL	Clemson University, GE Energy Consulting	$1.72M proposed over three years
Project 6: Operational and Strategic Implementation of Dynamic Line Rating for Optimized Wind Energy Generation integration	Idaho National Lab's concurrent cooling–Dynamic Line Rating (DLR) is an example of additional data that needs to be effectively integrated into control rooms. The DLR project supports the DOE Office of Energy Efficiency and Renewable Energy (DOE-EERE) mission to provide high-impact research, development, and demonstration to make clean energy as affordable and convenient as traditional forms of energy by establishing a means to increase the integration of renewable	INL	Idaho Power Company, WinSim, Altalink, Alberta Electric System Operator, StormGEO, Stantec	$2.35M proposed over three years

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
	energy generation with the associated increase in transmission line capacity, which are traditionally limited by conductor thermal capacity and can be significantly underutilized. These projects take a science-based approach to advance line rating standards through an innovative methodology. These projects also develop various technology improvements utilizing dynamic, real-time environmental conditions measured and modeled using computational fluid dynamics, leading to average line capacity improvements of 10–40% above static ratings. The weather station data and ampacity calculation comprise an additional layer of data. Utilities would like to utilize this new capacity to enable additional power flow when the need to transmit power coincides with conducive meteorological conditions (concurrent cooling). Conveying the information to allow the operator to make an informed decision based on this additional information is important to more effective utilization of the transmission asset. Even more important is the timely notification when conditions change in a negative direction as the extra capacity is actively being used.			
Project 7: Pan North American Renewable Integration Study (PARIS)	The Pan North American Renewable Integration Study will address a major shortcoming in previous studies that only analyze high penetrations of renewables in one country. High penetrations of wind, solar, and hydro in the U.S., Canada, and Mexico could have substantial impacts on the design and operation of the power grids of each country, and analysis will be necessary to determine the potential operational impacts and the benefits of coordinated planning and operation between the three countries. PARIS will be the single largest renewable integration study ever undertaken.	NREL	Natural Resources Canada, SENER	$1.8M proposed over three years

Advanced Grid Modeling

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Project 1: Open-Source High-Fidelity Aggregate Composite Load Models of Emerging Load Behaviors for Large-Scale Analysis	This work proposes to develop a set of regional–level, scalable open source load models and tools, including large scale aggregate load protection, price responsive demand, advanced load composition data, and next generation load model data tools. The resulting improvements will significantly enhance the regional level power grid's overall stability and reliability	PNNL, LBNL	WECC, MVWG, LMTF, Southern California Edison, BPA	$2.4M proposed over three years
Project 2: Emergency Monitoring and Controls Through New Technologies and Analytics	Development a new generation of emergency control systems for the U.S. power grid based on a combination of new technologies, and new analytic capabilities related to recent progress in the power system reliability assessment translated into new real-time algorithms for voltage stability and transient stability. Compared to the existing configuration of the overall protection system, the proposed Coordinated Emergency Control System (CECS) will bring the following significant advantages: The CECS system will operate in real time, while its setting will be selected in near real time, will dynamically coordinate settings of the existing hierarchical protection from Zone 1 protection to SPS protection and involve additional control actions to the overall design, CECS system will adapt to changing system configuration and parameters, and the system will be more online and data-driven, and not just post event-analysis driven it will rely on new analytics.	LANL	ISO-NE	$3M proposed over three years
Project 3: Measurement-Based Hierarchical Framework for Time-Varying Stochastic Load Modeling	Leverage practical AMI, SCADA, PMU and laboratory experiment data to develop static, dynamic as well as customer behavior-driven and demand response-enabled load/DG models at component, customer, feeder and substation levels. The developed hierarchical load/DG models will facilitate the development of planning models and integrated transmission and	ANL	Iowa Energy Center, Siemens, Eaton, ComEd, Alliant Energy, MidAmerican Energy, ERCOT, PJM, City of Ames, Cedar Falls Utilities, Iowa State University, ISU's Electric Power Research Center	$2.7M proposed over three years

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
	distribution models (Topic 4). Successful completion of this project will deliver a set of load/DG models and commercially-available software tools (PSS/E, CYME, RTDS/OPAL-RT) with the developed models.			
Project 4: Protection and Dynamic Modeling, Simulation, Analysis, and Visualization of Cascading Failures	Develop and validate a dynamics and protection simulation platform to enable utility planning, operations, and protection engineers to better understand and mitigate cascading blackouts involving protection. To realize this goal, the team will build upon the capabilities of 'TS3ph', a dynamics simulator developed through the DOE-OE AGMR funded project "High-fidelity 'faster than real-time' simulator for predicting power system dynamic behavior." The project will focus on advancing the modeling, simulation, analysis, and visualization capabilities of TS3ph-CAPE through the following innovation pathways: Fill current industry modeling gaps, accelerate dynamics simulation, develop new analysis metrics, create new situational awareness capabilities, and validate and verify the developed dynamics simulator with standard industry tools, and observed data.	ANL	Illinois Institute of Technology, Electrocon International Inc., McCoy Energy, Iowa State University, ComEd, AltaLink, SPP	$2.48M proposed over three years

Advanced Distribution Management Systems

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Project 1: Development of an Open-Source Platform for Advanced Distribution Management Systems	An initial version of an open source integrated software platform for varying vendor systems will be developed which supports the full suite of distribution management applications (such as voltage and reactive power optimization; fault location, isolation, and service restoration; economic dispatches; and optimization routines). This integrated platform, based on specifications and requirements to be developed jointly with utilities, will allow information to flow between individual applications across the entire utility enterprise, enabling enhanced visibility and controllability of system assets. Development and evaluation of the ADMS platform will be conducted in a utility-	PNNL, NREL	Washington State University, Incremental Systems, Modern Grid Solutions	$13.5M proposed over 3 years

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
	centric environment, involving qualified system operators from distribution utilities of varying sizes, to ensure that the capabilities being developed are applicable to the largest possible cross section of utilities. Investments leveraging the increased types and volume of available system data, due to a recent surge in advanced technology deployments, will also be explored to develop new applications. These new applications will greatly enhance observability and controllability required to integrate large amounts of renewables in a safe and effective manner, utilize assets more efficiently during restorations, enable much wider range of choices for consumers, and maintain affordable electricity rates.			
Project 2: Development of an Open-Source Platform for Advanced Distribution Management Systems	The aim of this project is to develop a modular, hierarchical ADMS application that engages DERs to (1) regulate network constraints and optimize distribution-level objectives such as resistive losses, nodal voltage magnitudes, and customer costs and (2) provide transmission-level services to improve bulk grid reliability and facilitate renewables integration through increased grid flexibility.	LBNL	Riverside Public Utility, Smarter Grid Solutions	$3.25M proposed over 3 years
Project 3: Advanced Distribution Management System Testbed Development	This project will establish a national, vendor-neutral Advanced Distribution Management System testbed to accelerate industry development and adoption of ADMS capabilities for the next decade and beyond. The testbed will enable utility partners, vendors, and researchers to evaluate existing and future ADMS use cases in a test setting that provides a realistic combination of multiple utility management systems and field equipment. The testbed will allow utilities and vendors alike to evaluate: (1) the impacts of ADMS functions on system operations; (2) interoperability among ADMS system components; (3) interactions with hardware devices; (4) integration challenges of ADMS with legacy systems; and (5) ADMS vulnerability and resiliency. The testbed will provide a less expensive and lower risk alternative to a pilot deployment, plus the ability to simulate contingency scenarios that are not practical to test using a real distribution system.	NREL, PNNL, ANL	EPRI, ALSTOM Grid Inc., Schneider Electric, Opal-RT Technologies	$4.5M proposed over 3 years

Energy Systems Risk and Predictive Capabilities

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Project 1: Improved Forecasts of Electric Outages from Tropical Cyclones	Improve forecasts of electric outages for tropical cyclone events affecting U.S. territory in the Caribbean, Atlantic seaboard, and Gulf of Mexico regions. The project is intended to design a web-based tool that would forecast potential electric distribution outages from tropical cyclones on a county block level and to identify energy system infrastructure at-risk.	ANL	Meade Electric, Georgia Power/ Southern Company	$0.8M proposed over two years
Project 2: Recommendations for the Population, Location, and Operation of a Strategic Transformer Reserve	This project will investigate the potential of a Federal strategic reserve, proposed in H.R.2244, to provide spare transformers in times of extreme events by determining the number and assortment of spare transformers required to recover from extreme events in a timely manner, optimal number and location of storage facilities, transportation logistics, and recommendations for withdrawal practices.	ORNL, SNL	University of Tennessee-Knoxville, EPRI, SNL, Dominion Virginia Power Industry	$1.3M proposed over 1 year
Project 3: Web Tool for Improved Electric Outage Forecasting for Response to Tropical Cyclone Events	Develop and deploy an online software tool available to the DOE Emergency Operations Center (EOC) analysts that enables them to make repeatable predictions of electrical outages caused by imminent or synthetic tropical cyclones at a spatial resolution of 250m X 250m with quantified uncertainty. The online software tool will also identify critical infrastructure at risk from direct cyclone impacts and secondary impacts from electric power outages.	LANL	University of Michigan, Texas A&M	$0.7M proposed over two years

Energy Storage

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Project 1: Energy Storage Demonstrations - Validation and Operational Optimization	Collaborate with states, utilities, and storage providers to help elucidate storage benefits and integration challenges. Specifically, work with four demonstration projects that cover a wide range of promising technologies and applications: Green Mountain Power (VT), Salem Smart Grid Center (OR), Electric Power Board (EPB) of Chattanooga (TN), and Los Alamos	SNL, PNNL, ORNL		$2.5M proposed over two years

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
	County (NM). The outcome will be analysis that identifies the value streams for each potential application, as well as operational modes and control strategic for the optimal utilization of the energy storage system to maximize the value streams.			
Project 2: Collaborative Demo for Secondary Use and Use Case Validation	Develop and examine the business case for a residential based deployment of secondary use energy storage, deploy and commission a secondary use energy storage system to bring industry acceptance and validation of the business case, drive the future of secondary use energy storage systems with advanced supporting control algorithms, and disseminate information to stakeholders.	ORNL	Spiers New Technologies, Habitat for Humanity, Central Carolina Community College	$1.2M proposed over three years

Smart Grid

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Project 1: LPNORM: A LANL, PNNL, and NRECA Optimal Resiliency Model	Develop and deliver a software tool called LPNORM for designing resilient distribution grids to support meeting the MYPP goal and DOE major outcome of a "10% reduction in the economic costs of power outages by 2025." This tool is a novel combination of existing and new capabilities. LPNORM will allow users to import distribution and communication models, specify extreme weather events, specify resiliency criteria, and verify design solution quality with trusted power flow solvers.	LANL, PNNL	NRECA, University of Michigan	$1.8M proposed over three years
Project 2: A Closed-Loop Distribution System Restoration Tool for Natural Disaster Recovery	Develop a distribution restoration decision support tool that will assist utilities in performing distribution restoration after extreme weather events in an optimal and efficient manner. The tool will integrate the weather information/forecasts and system fragility assessment together with the field measurement data for improved situational awareness and system damage estimates, employ advanced optimization models for dispatch of repair crews and associated resources, and utilize distribution automation to reconfigure distribution grids and pick up loads promptly to reduce the outage sizes and durations. The closed-loop feature of the proposed tool will make the tool adaptive to the evolving weather events and varying restoration capabilities.	ANL, BNL	Iowa State University	$1.95M proposed over three years

Transmission Reliability

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Project 1: Discovery Through Situational Awareness (DTSA)	Produce a prototypical, interactive situational-awareness tool to provide data visualizations and identify anomalous grid behavior, allowing the user to explore any of the data. The research will look for precursors to unusual grid behavior and then apply machine-learning algorithms to help understand what happens around these unusual grid behaviors. Interactions with our industry partners will help fine-tune these algorithms. This project will advance the state-of-the-art and provide insights that can benefit the industry	PNNL	MISO Energy, ISO New England, PJM, NYISO	$0.67M proposed over one year
Project 2: Suite of Open-Source Applications and Models for Advanced Synchrophasor Analysis	Research to develop a suite of software applications and libraries of phasor measurement units (PMUs) and synchrophasor data for power system planning, modeling, and analysis. The research and software development activities will be coordinated with industry partners and universities. All applications will be based on the common open platform concept, have a common data format structure, and be released under an open-source license. This work will address oscillation detection, frequency response, model validation and calibration, equipment misoperations, and other important power-grid-related issues.	PNNL, LBNL	LBNL, BPA, WECC, JSIS, MVWG, NERC Resources Subcommittee, University of Wyoming, Binghamton University, Montana Tech, University of Wisconsin-Madison	$0.6M proposed over one year
Project 3: HVDC and Load Modulation for Improved Dynamic Response Using Phasor Measurements	Investigate ways to use the information available from phasor measurement units (PMU), and the widespread availability of controllable loads, to design a novel control strategy for inter-area damping. The first part of the proposed work will develop a decoupled modulation control approach to design a more effective damping control with less interference among different oscillation modes in the system. The second explores how HVDC networks and a sufficient proportion of the loads could be used to enhance the decoupled modulation control approach developed in the first part.	PNNL, SNL	Arizona State University, Pennsylvania State University, BPA	$0.7M proposed over one year

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
	Methods to enhance measurement redundancy and control in case of PMU communication failure will also be developed.			
Project 4: Advanced Machine Learning for Synchrophasor Technology	Develop a suite of new Grid-Modeling aware Machine Learning (ML) tools to monitor the transmission grid during its normal operations (task 1) and also localize significant frequency events in seconds after they occur (task 2). They will utilizes (a) advanced optimization and computation methods and algorithms for ML and data analytics; (b) the state-of-the-art, industry-grade frequency monitoring software; (c) phasor measurement unit (PMU) measurements at the transmission level; (d) aggregated micro-synchrophasors (uPMU) measurements at the distribution level; and (e) modern map-visualization tools and approaches. They will build new ML software to provide situational awareness, computational, and map-visualization extensions of the PNNL & BPA Power Plant Model Validation (PPMV) software.	LANL	BPA, JSIS, OPE Energy Corporation, Riverside Public Utilities	$3M proposed over three years

Transformer Resilience and Advanced Components

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Project 1: Models and Methods for Assessing the Value of HVDC and MVDC Technologies in Modern Power Grids	This project will concentrate on exploring scenarios and use cases, including multi-objective DC system modulation/control strategies for providing artificial inertia to the system and simultaneously to provide an optimal redistribution of power flows in the AC system to accommodate additional flows from renewables in a reliable and economical fashion. The key element in the approach is to maximize the value of DC technologies by exploiting their advantages in a coordinated fashion.	PNNL, ORNL	MISO, SPP, Entergy, Siemens	$0.8M proposed over one year
Project 2: Advanced Modeling of Land-Based and Subsea HVDC/MVDC	The focus of this proposed effort is to develop a comprehensive set of transient and dynamic models for HVDC/MVDC transmission	NREL, LLNL, SNL	EPRI	$2.7M proposed over three years

Confidential

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Transmission System	topologies, and hybrid simulation interfaces that can be used for stability and reliability analysis of DC-transmission dominated power systems with high levels of variable renewable generation. The availability of such models will enable the research community to investigate the impacts of control characteristics of HVDC/MVDC systems and address the challenges listed under several GMLC Foundational Topics.			
Project 3: High Voltage Testing and Modeling of Transformer, Line Interface Devices, and System Components Under Electromagnetic Pulse, Geomagnetic Disturbance, and Other Abnormal Transients	This project consists of both the modeling and testing efforts that will help understand physics behind how GMD and EMP impact key components such as transformers in power grid and what damages they may cause. The first year will focus on the analytical and numerical modeling of the physics behind the GMD/EMP's impacts to power grid components. The second year will focus on the testing-based study of the mechanism of insulation failure under short-duration EMP transients. And the third year will focus on the testing-based analysis of the multi-physics coupling of transformers under long duration transients (EMP E3 and GMD).	ORNL, LLNL	EPRI, Dominion, University of Tennessee, University of Wisconsin	$2.2M proposed over three years

Cybersecurity for Energy Delivery Systems

PROJECT NAME	DESCRIPTION	LAB	PARTNERS	FUNDING
Project 1: MultiSpeak® - Secure Protocol Enterprise Access Kit (MS-SPEAK)	The objective of this project is to fill a gap and make the grid "smarter" (i.e. more intelligent and resilient) through the creation of an innovative ESB+ (enterprise service bus) for MultiSpeak. The ESB+ will support increased interoperability and security of the MultiSpeak standard and reduce costs in utilities that depend on MultiSpeak. ESB+ will include a number of game changing advances.	PNNL	NRTC, NRECA	$1.65M proposed over three years
Project 2: Cybersecurity for Renewables, Distributed Energy Resources, and Smart Inverters	The objective of this project is to develop a holistic attack-resilient architecture and layered cyber-physical solution portfolio to protect the critical power grid infrastructure and the integrated distributed energy resources (DER) from malicious cyber-attacks. The project will help ensure the large-scale and secure integration of DER to the power without harming the grid reliability and stability.	ANL	WSU, EPRI	$1.8M proposed over three years

Program / Project Synopsis – DOE

Sensor and Modeling Approaches for Enhanced Observability and Controllability of Power Systems with Distributed Energy Resources

The focus of the FOA is to capture the benefits commonly attributed to DERs and/or microgrids, as well as to establish new value propositions that could be enabled by low cost sensors and improved modeling that uses sensor data input. New value propositions could include, but are not limited to, mitigating ancillary resource requirements and meeting growing demands for reliable and resilient grid operations against outages under all-hazards conditions.

Enabling Extreme Real-Time Grid Integration of Solar Energy (ENERGISE)

As part of the Department of Energy's Grid Modernization and SunShot Initiatives, this Enabling Extreme Real-Time Grid Integration of Solar Energy (ENERGISE) Funding Opportunity Announcement (FOA) supports the research and development of highly scalable distribution system planning and real-time operation solutions that enables seamless interconnection and integration of high penetration solar generation onto the electricity grid in a cost-effective, secure, and reliable manner. The envisioned ENERGISE solutions will require the extensive use of sensor, communication, and data analytics technologies to gather up-to-the-minute measurement and forecast data from diverse sources and perform continuous optimization analysis and active control for existing and new PV installations in real time. The solutions need be compatible with the existing grid architecture in the near term and with the advanced grid architecture in the long term. The solutions should also be designed with consideration of the interoperability and cybersecurity requirements.

Synchrophasor Applications and Tools for Reliability and Asset Management

The objective of this Funding Opportunity Announcement is to support the industry's transition to technologies led by time-synchronized, high-speed measurements, which from this point forward will be referenced as synchrophasor technologies. Synchrophasors will affect the evolution of the US grid by improving system reliability, increasing the utilization of existing transmission assets, and improving the efficiency of wholesale market operations.

Cybersecurity for Energy Delivery Systems Research Call

DOE Office of Electricity Delivery and Energy Reliability (OE), is seeking applications for high-risk, high-payoff, research, development and demonstration of technologies and techniques that advance the state-of-the-art, offer new capabilities not available today, and that will be widely adopted for use throughout the energy sector to further strengthen cybersecurity of the U.S. energy delivery infrastructure.

Solar Energy Evolution and Diffusion Studies II - State Energy Strategies (SEEDSII-SES)

This Funding Opportunity Announcement (FOA) aims to reduce the soft costs of solar deployment through two approaches, referred to as Topic 1 and Topic 2 in the FOA. The first topic, "Topic 1" is targeted at increasing our foundational understanding of technology evolution, soft costs, and barriers to solar deployment in the US. By combining cutting edge research tools with the creation, analysis and functionalization of data and information, this second round of the Solar Energy Evolution and Diffusion Studies (SEEDS) program will examine how solar technologies, the electric grid system, and the institutions that create the solar business marketplace support or impede the evolution and diffusion of solar by partnering researchers with data and energy practitioners. "Topic 2" will directly tackle soft costs and market barrier challenges at the state and regional level by maximizing the benefits of solar electricity through energy and economic strategic planning. This program targets partnerships between states and utilities/electricity sector entities that look to increase solar deployment in their region. This will be achieved through analytical support to develop and implement strategies to: determine or expand renewable energy and other goals, such as: maximizing emissions reductions; hedging against fuel price volatility; creating jobs; expanding access to electricity; and/or increasing grid resiliency, among others.

Addressing Risk and Uncertainty in the Future Power System
The nation's wholesale electricity markets and transmission planning are in a state of transition. The Department of Energy's (DOE's) Office of Electricity Delivery and Energy Reliability (OE) is interested in both operational and planning modeling and computation methodologies/techniques needed to support the future engineering and market functions required by these systems. Addressing risk and uncertainty is central to meeting the needs and ensuring reliability is a fundamental requirement of the system. There are three research areas for this Funding Opportunity Announcement (FOA): a) wholesale market operations, b) transmission planning, and c) demand-side participation.

Industry Partnerships for Cybersecurity of Energy Delivery Systems (CEDS) Research, Development and Demonstration for the Energy Sector
The Office of Electricity Delivery and Energy Reliability (OE) is seeking applications under this Funding Opportunity Announcement (FOA), herein referred to as Announcement, to conduct research, development and demonstrations (RD&D). This RD&D will lead to next generation tools and technologies that will become widely adopted to enhance and accelerate deployment of cybersecurity capabilities for the U.S energy infrastructure, including cyber secure integration of smart grid technologies.

SunShot Technology to Market (Incubator Round 11, Solarmat Round 4)

The purpose of this funding program is to help remove barriers that are addressable by technology and business innovation. These solutions cover hardware innovation and manufacturing, software, cost-reductions throughout the value chain, and non-cost (capability) related solutions. These solutions are expected to aid in achieving a ubiquitous solar energy solution and provide a clear path for these highly impactful technologies and solutions to rapidly reach market success. This funding program seeks to fund for-profit entities to develop products and solutions which will further reduce the price of solar energy and de-risk the integration of solar energy to the electricity grid.

GRID MODERNIZATION LAB CALL
The lab call constituted of the Department's Activities for the Grid Modernization Initiative in FY2016. Offices to the lab call include the Office of Electricity and Energy Reliability, the Office of Energy Efficiency and Renewable Energy, and the Office of Energy Policy and Systems Analysis. Since only DOE National Laboratories were eligible to apply as primary recipients under this Lab Call, the awards issued were through the Work Authorization System based on a Field Work Proposal (FWP), an Inter Entity Work Order (IWO), an Annual Operating Plan (EERE) or other allowable instrument deemed appropriate by the Government.

Design Support Tool for Remote Off-grid Microgrids
Office of Electricity Delivery and Energy Reliability (OE), is seeking proposals for research and

development (R&D), testing, and transitioning into practice of a design support tool for remote off-grid microgrids. An overarching goal of this Research Call (Call) is that the developed tool must be capable of providing decision support analysis on AC (alternating current) and DC (direct current) microgrids to meet user-defined objectives and constraints for costs and energy system security. The tool developed as a result of this Call must facilitate the design of microgrids that encompass mixes of generation assets and load profiles that are typical of remote communities; and be capable of conducting such analyses as may be necessary to validate that corresponding design parameters, planned operational performance and expected benefits of microgrids can be achieved effectively and economically. The developed tool should be readily usable by designers of microgrids for off-grid applications in remote communities and should be useful for the DOE in evaluating all remote microgrid applications.

Academic Collaboration for Cybersecurity of Energy Delivery Systems Research and Development for the Energy Sector
Office of Electricity Delivery and Energy Reliability (OE), is seeking applications for an academic collaboration with expertise in power system engineering and cybersecurity computer science to innovate and transition cybersecurity capabilities to the energy sector to reduce the risk of power disruption resulting from a cyber-incident.

The Resilient Electricity Delivery Infrastructure (REDI) Initiative
The Resilient Electricity Delivery Infrastructure (REDI) InitiatThe Resilient Electricity Delivery Infrastructure (REDI) Initiative is a Department of Energy (DOE) action that focuses on technology transfer of smart grid advances to support the White House initiatives responding to the needs of communities nationwide that are dealing with the impacts of climate change. Through the REDI initiative, the DOE Office of Electricity Delivery and Energy Reliability (DOE-OE) is providing opportunities to deploy smart grid technologies/tools to improve climate preparedness and resiliency of the electricity delivery infrastructure.

SunShot Technology to Market (Incubator Round 10, SolarMaT Round 3, SUNPATH Round 2)
The purpose of this funding program is to help remove barriers that are addressable by technology and business innovation. These solutions cover hardware innovation and manufacturing, software, cost-reductions throughout the value chain, and non-cost (capability) related solutions. These solutions are expected to aid in achieving a ubiquitous solar energy solution and provide a clear path for these highly impactful technologies and solutions to rapidly reach market success. This funding program seeks to fund for-profit entities to develop products and solutions which will further reduce the price of solar energy and de-risk the integration of solar energy to the electricity grid

Sustainable and Holistic Integration of Energy Storage and Solar PV (SHINES)
The SunShot Initiative (SunShot) is a national collaborative effort to make solar energy cost-competitive with other forms of electricity by the end of the decade. The installed cost of solar photovoltaics (PV) has reduced significantly in recent years, spurring significant and accelerating deployment of PV systems. With the anticipated proliferation of solar power at the centralized and distributed scales, the variability and uncertainty of the solar resource poses challenges for reliably integrating photovoltaics (PV) with electric power systems, both at the distribution and bulk system levels.

The goal of the Department of Energy, Energy Efficiency and Renewable Energy, SHINES Funding Opportunity is to enable the development and demonstration of integrated, scalable, and cost-effective technologies for solar that incorporates energy storage and works seamlessly to meet both consumer needs and the needs of the electricity grid. Such an integrated solution should utilize smart inverters, and be capable of working with smart buildings, smart appliances, and utility communication and control systems. The solutions thus developed will enable widespread sustainable deployment of low-cost, flexible, and reliable PV generation, and provide for successful integration of PV power plants with the electric grid.

Program / Project Synopsis – EPRI

Distribution

Develop new tools, enhanced methods, and the technical basis to plan, operate and maintain a more modern, integrated distribution system that combines the benefits of advanced grid technologies and distributed energy resources to yield a more efficient, reliable, and customer-centric grid.

94 - Energy Storage and Distributed Generation

Program Description

This program covers research related to energy storage, fueled distributed generation (DG), and microgrid technologies. The scope covers energy storage connected to utility transmission system, distribution system, and customer premises. It also covers fueled DG of less than 10 MW capacity, such as fuel cells or combined heat and power (CHP) connected to the utility distribution system or customer premises. These technologies may provide a range of benefits to the power system, including enhanced power quality, reliability, avoid costs to grid infrastructure, operational efficiency, and greater integration of variable, renewable resources. Depending on location and usage, these benefits may be "stacked" and shared across multiple stakeholders, which can create opportunities, as well as challenges, to realize the full potential of these technologies.

The research covers and integrates multiple activities, including technology evaluation, economic and technical modeling to support grid planning and operations, and field demonstration. The current program mission is to facilitate availability and use of energy storage technology options and integration strategies which support safe, reliable, affordable, and environmentally responsible electricity.

Research Value

Energy storage and distributed generation technologies may result in higher reliability for power systems and customers, increased deployment and utilization of renewable energy, and improved affordability of electric power under various scenarios. The outputs of this research are expected to support the following outcomes:

- Improved understanding of the fast-evolving state of energy storage and DG technology development, relative to expectations and requirements for power system applications to utilities and end customers.

- Development of collaborative approaches for utilities and industry participants to improve communication, lower project soft costs, and promote safety and reliability of energy storage deployments.
- Development of economic and technical evaluation methods and tools to guide location, design, and operations of energy storage, DG, and microgrid technologies, which support value maximization and cost reductions for society.

Approach

The research program utilizes the following approaches:

- Investigate current state and trends shaping the potential value and applications for energy storage and DG, including technical, regulatory, and commercial drivers.
- Evaluate energy storage and DG technology cost, performance, safety, and technology readiness level, relative to the needs of intended applications.
- Collect testing and demonstration performance data and investigate real-world cost, performance, safety, and reliability of technologies.
- Investigate current practices related to energy storage and DG deployment, and convene stakeholders to uncover challenges which may be addressed through collaborative research.
- Leverage investigation of research questions with various existing projects to leverage technology hardware for maximum learning.

As energy storage technology has evolved from an R&D topic to commercial projects in the last 5 years, the needs and focus of the research program evolves to address the next generation of research questions. Since 2010, the research program has devoted resources to understanding the value of energy storage in specific instances. This remains a focus, but as the prevalence of commercial energy storage projects increases, the research addresses topics further into the lifecycle of projects, including the considerations of performance and reliability, maintenance practices, project safety, and end-of-life considerations.

This research program is cross-disciplinary and collaborative with other research programs and institutions to address the broad set of challenges and opportunities associated with quickly emerging resources to support power systems and customers. Increased detail on research pertaining to techno-economic analysis, performance and reliability, and implementation considerations is provided below:

- Develop advanced models capable of optimization and simulation to evaluate value propositions and grid impacts of energy storage and DG.
  - Develop techno-economic optimization and simulation models, such as the Storage Value Estimation Tool (StorageVET) and microgrid and distributed energy resources (DER) valuation model, to accurately assess value and support optimization of project design and usage.
  - Investigate integration of storage and microgrid into current planning and operations models to support seamless consideration of new technologies.
  - Perform detailed case studies and share modeling lessons learned and benchmark with field data, with leveraging government-funded and supplemental projects.

- Specify methods and evaluate societal benefits and costs which may be more difficult to assess, such as greenhouse gas impacts and lifecycle analysis, in collaboration with other research programs.
- Advance guidelines for benefit-cost analysis assessment to improve understanding and communication of energy storage and DG costs and benefits.

- Investigate technology cost and performance that may change value propositions.
  - Investigate relationships and sensitivities of technology cost and performance to the applications and lifecycle value of energy storage.
  - Investigate early stage R&D activities and potential to materially affect value propositions of new technology deployments.
  - Communicate research results pertaining to target attributes with technology developers and labs to improve knowledge of power system and end customer needs and targets.
- Evaluate energy storage, DG, and microgrid deployment experiences and challenges.
  - Evaluate the current codes and standards environment for energy storage and the gaps or inconsistencies.
  - Develop scientific data, evaluation plans, and technology transfer plans to inform future codes and standards for safety of new deployments.
  - Create and leverage common guidelines that support safe and reliable projects, through EPRI's Energy Storage Integration Council (ESIC).
- Measure and analyze performance, reliability, and safety-related data of projects in laboratory and field contexts.
  - Utilize common testing and evaluation procedures for consistent and comparable datasets (ESIC Test Manual).
  - Evaluate real-world performance of technologies in the context of desired attributes and project performance expectations.
  - Build a data and experience track record of performance and reliability over time to understand implications on project lifecycle costs and benefits.
  - Measure economic performance of projects relative to modeled economics, and evaluate underlying cause for differences in outcomes.
- Continuous update and refinement of tools, methods, datasets, guidelines and best practices for future projects.
  - Collect and analyze datasets to support accurate assumptions related to technology, function, performance, and cost.
  - Refine models to better approximate real-world energy storage operational conditions.
  - Build and disseminate best practices and guidelines to support mass-customizable implementations of energy storage and DG to support a vision of safe, reliable, affordable, environmentally-responsible electricity.

Accomplishments

- Storage Value Estimation Tool (StorageVET®) - A web-hosted optimization and simulation software was developed to support understanding of energy storage benefits and costs. It supports optimization of energy storage project location, design, and operations. StorageVET has been used by over 1800 individuals and is currently being applied to dozens of case studies. In 2018-2019, StorageVET was recoded and released as an open source tool to enable broader usage and collaborative coding development. More information at www.storagevet.com. Previous iterations of this valuation research informed California policy decision-making. A report called Cost-Effectiveness of Energy Storage in California (EPRI 3002001162) was published.

- Energy Storage Integration Council (ESIC) - an active technical forum hosted by EPRI to bring together 2,000 industry participants from utilities, energy storage developers, and the research community to identify and develop guidelines and templates to support clear interactions that support safe, reliable, and cost-effective energy storage products. To date, ten published guidelines, tools, and templates have been published with regular updates. More information at www.epri.com/esic.
- Energy Storage Technology and Cost Assessment - A cross-program initiative, led by Program 94, developed a cost analysis for energy storage across multiple technologies and design and configurations, along with an assessment of projected cost reductions to the year 2030. Through this study, EPRI developed a common template of cost line items for complete energy storage projects to facilitate broader consistency in cost comparisons, and to investigate cost trends within individual subsystems.
- Energy Storage Technology Database - In collaboration with EPRI Program 66, developed a website to house various scouting activities and evaluations of energy storage technologies on a rolling basis.
- DOE-EPRI Energy Storage Handbook - In 2013 and 2015, EPRI collaborated with the U.S. Department of Energy (DOE), the National Rural Electric Cooperative Association, (NRECA), Sandia National Laboratory, and several other stakeholders including a number of utilities, to develop the DOE-EPRI Energy Storage Handbook. Distributed free to the public from Sandia National Laboratory, this handbook is a comprehensive introduction to designing, procuring, installing, and operating utility-scale energy storage systems, and serves as a resource to utilities, vendors, and other stakeholders in the utility energy storage area.

Key Activities

- Project valuation analysis - Advance and apply methods and tools for techno-economic analysis of energy storage to investigate optimal siting, design, and operations for energy storage projects. Support various other analysis scopes for T&D planning, operations, generation planning, and grid future studies, in collaboration with subject matter experts in relevant programs.
- Energy storage performance and reliability assessment - Develop databases, collect data and perform analysis to understand operational performance, reliability, and lessons learned from energy storage demonstration and testing experiences.
- Emerging technology assessment - Investigate precommercial technologies for cost, performance, safety, and technology readiness. Leverage supplemental and government initiatives to test and demonstrate projects.

- Advance implementation guidelines - Identify gaps in energy storage implementation and work collaboratively with diverse participants to develop guidelines and tools through the Energy Storage Integration Council (ESIC).
- Develop methodologies to advance energy storage operational controls, focusing on multiple-use applications. Utilize EPRI Storage Value Estimation Tool (StorageVET®) and other modeling approaches. Develop and test control algorithms.
- Degradation modeling - Develop battery storage state-of-health (SOH) and state-of-charge (SOC) models to support reliable usage. Inform maintenance practices and project lifecycle planning.
- Investigate energy storage safety hazards, threats, and consequences, as well as potential barriers and mitigations to support safe energy storage project lifecycle. Identify gaps and potential approaches to energy storage safety incident response, with particular focus on battery storage fire events, to inform protection approaches for public and first responders.
- Investigate and end-of-life considerations of energy storage, including recycling and reuse, in collaboration with EPRI Program 197.
- Investigate integration of energy storage into utility distribution planning practices, including the synergistic usage of StorageVET and various tools for hosting capacity and interconnection assessments.
- DER and microgrid valuation and optimization - Extend methodologies used in StorageVET to advance consistent and validated approaches for cost-benefit evaluation across a range of DER and microgrid scenarios, in collaboration with a range of different EPRI programs.

Estimated 2020 Program Funding $5.0M

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PS94A: Strategic Intelligence and Industry Collaboration

This project set supports research to investigate key trends and developments in the rapidly evolving area of energy storage, distributed generation, and microgrids. It facilitates information exchange and collaborative efforts between EPRI members and with industry stakeholders to better understand the current state of the industry and prioritize research questions. This project investigates current state, drivers, and transfers key research results, including the technology advancements, commercial deployment activity, policy and regulatory developments, and integration challenges.

Examples of recent significant shifts that have occurred in the energy storage landscape include:

- Costs of lithium-ion based battery storage have dropped approximately 80% since 2010 and solar plus storage power purchase agreements (PPAs) are observed at record low costs with strong downward trends.
- Regulatory jurisdictions, including several U.S. states, Canadian provinces, and nations in Europe and Asia, have policy incentives or procurement targets for energy storage, and other jurisdictions are evaluating a range of policy options to direct consideration, or to incentivize, energy storage deployments.

- In the U.S., FERC Order 841 was issued in 2018. The order establishes a participation model for energy storage in organized markets, allowing storage to participate in energy, ancillary services, and capacity markets when technically able. These new markets are expected to be active in 2020.
- A dynamic and growing industry, including dozens of new suppliers, is driving new energy storage, several have been bought or merged with other companies, and some have exited.
- Emerging codes and standards and recent fire safety incidents have spurred an increased focus on safety.

P94.011: Strategic Intelligence and Knowledge Exchange

The landscape for energy storage, distributed generation (DG), and microgrids is evolving rapidly. Because these technologies are not yet commonly integrated into the electric power system, changes in the landscape have the potential to substantially alter the future deployment and use. This project seeks to understand the current state and drivers for these technologies and the implications on their future value propositions. These drivers include policy and regulatory developments, evolving power system needs and societal drivers, updates in grid codes and standards, technology cost, and technology performance trends.

P94.012: Energy Storage Integration Council

Energy storage is an emerging asset class, and utilities and other users have limited experience in understanding how it fits into planning and operations. The recent acceleration in energy storage deployments is exposing challenges for utility safety, reliability, internal planning, and operational processes. The range of challenges are exposed through real-world experiences across a wide range of energy storage projects. In order to understand gaps and potential solutions, the various stakeholders can accelerate progress through regular, structured interactions. The purpose of this project is to regularly engage stakeholders to explore and report on-the-ground integration experiences and challenges, and to define scopes of work for projects which may be collaboratively executed to help all stakeholders improve safety, reliability, and reduce soft costs in future projects.

This project supports the Energy Storage Integration Council (ESIC), an open, cross-stakeholder collaborative technical forum with a mission to advance the integration of energy storage, guided by the vision of safe, reliable, affordable, and environmentally-responsible electricity.

PS94B: Technology, Economics, and Integration

Energy storage is a flexible technology and may provide multiple value streams to the electric power system and end customers. Use cases for energy storage may provide value and impacts to multiple stakeholders, creating both opportunities and challenges. Energy storage has unique attributes and limitations that must be appropriately characterized to be incorporated into tools and practices that support efficient and informed decision making for grid planners and operators.

Energy storage technologies span a range of media, including electrochemical, mechanical, thermal, electrostatic, and even electrofuels. A range of technologies are under consideration, and they may be incorporate either a standalone energy storage technology, or as a hybridized generation or end-use device. Batteries, in particular lithium ion batteries, have been dynamically evolving in cost and performance, due in part to a large industry investment in portable electronics and electric vehicles. Lithium ion is a diverse battery technology category with numerous variations in cathode, anode, electrolyte, separator, and cell architectures. All of these factors may affect cost, performance, and safety of energy storage projects, utilizing lithium ion technology. Other storage technologies, some widely used (e.g. pumped storage hydro) and some earlier stage (e.g. flow batteries), may have cost, safety, and reliability attributes which enable certain applications and evolutions in the use of energy storage.

This project set performs foundational research across a range of energy storage technologies and applications. It provides tools, methods, and research findings related to the following topics:

- Developing practical, repeatable, and validated methods to investigate energy storage site-specific value, as well as design and operations optimization.
- Applying methods for energy storage techno-economic analysis in a variety of cases
- Investigating the cost of energy storage projects with complete methodologies which enable lifecycle cost-benefit analysis of projects, as well as consistent comparisons with other technologies.
- Investigating existing and emerging energy storage technologies for key attributes, limitations, and development status, spanning performance, safety, reliability, and environmental considerations.
- Advancing methods for evaluating energy storage project control systems in a relevant and consistent manner and developing reference algorithms for individual and multi-use applications for energy storage projects.

P94.013: Energy Storage Valuation Analysis

This project investigates and advances methodologies and tools for cost-benefit analysis and supports optimization of location, design, and operations of energy storage projects. It also investigates the technical characteristics of energy storage technologies and the implications of modeling simplifications.

Energy storage has flexibility and functional characteristics which may not be fully considered in current valuation methodologies. It also has limited stored energy, which couples past operational decisions with capability to make future decisions. This characteristic is uncommon in conventional generation and T&D equipment, so the limited energy constraint is typically not considered in grid planning and operations methods.

Significant progress has been made in the methods and tools for performing site-specific energy storage value analysis, with the development of the Storage Value Estimation Tool (StorageVET®). However, application of StorageVET to many sites and regions has highlighted need for enhancements in input data, tool usability, and improvement in interpretation of results. Additionally, with numerous potential use cases and widely varying project value, numerous stakeholders are seeking answers to a variety of research questions that may require additional data availability, methodology guidance, and reference scenario development, in order to inform robust decision-making.

The key research questions for this project include:

- What are the use cases for energy storage valuation analysis, and what decisions do they inform?
- How are the various uses and potential value streams for energy storage quantified, in terms of performance requirements and economic value?
- What energy storage valuation methodologies and tools are in use and what are their limitations?
- What StorageVET® functionalities and interfaces may be developed to close gaps in valuation and communication of results?
- How does the lifecycle cost-benefit analysis of energy storage compare across different regions, reference use cases, and other factors?
- What are the key differences in results between similar modeling tools with identical input scenarios?
- How do modeled benefits of energy storage projects compare with real-world valuation findings?

P94.014: Energy Storage Technology Cost Analysis

It is important to accurately understand and compare the cost of energy storage options to conventional alternatives. Past studies have evaluated different scopes of cost, resulting in inconsistent (apples-to-oranges) comparisons. In a dynamic, early commercial environment, accurate and consistent cost comparisons and reference cost projections are important for the development of scenarios for analysis. A number of challenges exist that impede transparent understanding of energy storage cost:

- Energy storage cost structures are different from one technology to another.
- Energy storage costs scale by both rated power and rated energy, as well as other factors, complicating comparisons utilizing single metrics, such as dollars per kilowatt ($/kW) or dollars per kilowatt-hour ($/kWh).
- Different grid applications and site-specific circumstances have diverse operational duty cycles which affect specification and lifecycle costs.
- Up-to-date energy storage costs are often kept confidential by developers.
- Scope of supply for cost studies typically varies from study to study and is sometimes not clearly delineated.
- O&M and disposal costs are not well understood, due to the nascent track record of energy storage.

Utility planners often look 5-15 years ahead, and it is important to understand the approximate costs for energy storage projects now and in the future to determine whether energy storage may contribute to economic solutions. Cost alone is not sufficient; the capital and operational cost structure, coupled with valuation, is important for assessment of energy storage economics.

P94.015: Energy Storage Technology Assessment

Energy storage technologies are developing at a significant rate, commercially driven by portable electronics, electric vehicle, and increasingly the commercial emergence of stationary energy storage markets. Researchers and developers are pursuing new technologies, as well as enhancements to those which are currently commercially available.

Energy storage spans a number of potential media, including electrochemical (e.g. batteries), electromechanical, electrostatic, thermal, and hydrogen. Lithium ion batteries have constituted the majority of other technologies in the past few years, with significant cost and performance improvements, which are expected to continue for the foreseeable future. However, the cost structure, safety, and reliability aspects of lithium ion may limit certain applications for stationary grid storage in the future.

Broad scouting of new, emerging technologies and deep dives on higher technology readiness levels is needed to inform developments and facilitate advancement in grid storage applications. Technologies need to be investigated in the context of beneficial and required attributes for power systems, including safety, durability, cost, efficiency, environmental impact, and energy density.

P94.016 Energy Storage Deployment and Integration

Energy storage is a flexible asset, with the potential to provide a number of value streams to electric power system planners, operators, and end customers. With prior analysis of needs and appropriate design, storage projects may be able to "stack" multiple value streams to maximize value and utilization of the asset, include the provision of service to multiple stakeholders and domains, with shared value propositions.

These value propositions have been scouted and analyzed for several years, but most of the early deployments of energy storage have executed more basic use cases with only one to two simultaneous value streams. The vision of multiple stacked value streams and optimized value in operations is now a topic of major concern, which drives the need for this focused research project to investigate energy storage controls.

P94.017: Distribution Energy Storage Integrated Products and Projects

This project investigates research questions related to the integration of energy storage products and projects connected to the utility distribution system. Distribution-connected energy storage has the technical potential to enhance traditional distribution infrastructure, enhance power quality, accommodate renewables and other distributed energy resources (DER), and support grid resilience and reliability. It may also have the potential to combine, or "stack", multiple services, targeting both local distribution and bulk power system objectives. However, even as these systems promulgate there continue to be numerous challenges impeding efficient placement and beneficial operation of these new grid assets.

From an institutional perspective, the utility processes of planning, procuring, deploying, and operating these systems are still nonstandard and as a result, there are still hurdles to achieve and maintain desired safety, reliability, and economic viability. These hurdles can be classified in distinct areas including:

- Control and operation for distribution-connected energy storage systems is particularly challenging when pursuing multiple services with multiple stakeholders, which may require integration of many communication platforms and control systems.
- Safety concerns have been raised with some technologies based on sporadic incidents and the lag of safety standards and ensuing codes to keep up with the rapid pace of technology development
- Increased reliance on distributed resources, including storage, to play a central role in grid stability have raised attention on the cyber-security of these assets. These resources may have a non-traditional mix of ownership and operational responsibility that potentially includes an increased role for storage vendors in the operation of these assets. This then includes additional parties that play a role in ensuring cyber security dictates, that are in themselves evolving.
- Storage performance expectations are still being defined as there is relatively little widespread operational experience that allows true understanding of how these systems are expected to operate as they age, how their health is measured over time and how lack of performance is addressed not only via warranties but also field response to issues that arise.

This project aims to identify and address these challenges through a focus on:

- Refined integration requirements of storage into utility control systems.
- How safety standards are emerging and the specific impacts they are having on storage component and system design as well as system placement and operation.
- Continued survey of utility cyber-security dictates and how vendors are meeting those requirements.
- Assessment of the sophistication spectrum of storage reliability measurements where performance data acquisition, assessment and derivation of best operational practices are assessed from an owner/operator perspective.

This approach represents a continuous process that is informed and updated from previously analyzed gaps and associated lessons learned stemming from a variety of efforts, updated market assessments and new analysis to develop new tools and guidance documents and platforms. This project also serves to advance certain products of the Energy Storage Integration Council (ESIC) that address distribution energy storage issues.

The work being done in this project set collaborates with and is designed to complement the work undertaken in Information and Communication Technology (P161), Integration of Distributed Energy Resources (P174), Cyber Security (P183), Distribution Operations and Planning (P200) and Environmental Aspects of Fueled Distributed Generation and Energy Storage (P197).

P94.018: Distribution Energy Storage Modeling for Planning and Operations

As distributed energy resources (DER) are increasing deployed on the distribution system, utilities are challenged to mitigate impacts and maximize value. Energy storage is a potential tool to mitigate uncertainty and variability caused by DERs such as photovoltaics (PV) and can enhance the control of resources to serve as an alternative or complement to traditional upgrades. However, energy storage value and impact analysis is challenging within traditional cost and peak-load based planning approaches typically employed by distribution planners. Energy storage opportunities and issues, such as stacked benefits and limited energy, are challenging to fit into distribution planning frameworks. Planning tools historically have not included time-series analysis important for limited energy resources, nor do they bridge generation, transmission, and distribution, all of which are affected by the bidirectional dispatch of energy storage technology. The result is that storage systems may not be evaluated as potential solutions, or they may be deployed in sub-optimal configurations and locations. This has potential to reduce the overall value of the energy storage system and may result in power system reliability issues.

Advanced, yet practical, methodologies are needed to effectively integrate energy storage and other related DERs into distribution planning and operations. Improved prediction of the potential grid impacts, costs, and benefits are needed to support optimized energy storage project location, design, and operational strategies.

PS94D: Transmission Energy Storage

This project set advances research topics pertaining to energy storage connected to the high voltage transmission system. Its purpose is to develop and apply methodologies to evaluate and inform bulk storage technology development, analyze value and impacts to the transmission system over time, and to advance best practices for the integration and operations of projects.

Transmission energy storage has potential to provide flexibility and resilience to high voltage systems, as well as expand the potential for integration of higher levels of variable energy resources such as wind and solar. It may also enable more economical approaches to investment in generation and transmission infrastructure, through its potential to relieve constraints related to power flow and peak capacity through the time-shifting of energy. The flexibility of energy storage may also provide significant value as operational reserves, such as frequency regulation and spinning reserve.

Historically, energy storage deployments have primarily been large, transmission-connected pumped storage hydropower (PSH). In recent years, however, utilities have deployed hundreds of megawatts of new battery storage, primarily utilizing lithium ion batteries. The cost of lithium ion batteries, though continuing to decrease, may not fall low enough to enable cost-effective application of lithium ion batteries for long duration energy storage, which may become important in very high renewable scenarios in the coming decades. Certain technologies, with the potential for relatively lower cost than lithium ion batteries, may become viable, such as large-scale gravity concepts, compressed air, flow batteries, thermal storage, or hydrogen. These technologies may be deployed as standalone facilities or integrated into thermal or renewable generation facilities. Other concepts may include the development of fuels or flexible electrification as part of a holistic Integrated Energy Network.

Declining costs and system performance requirements (such as decarbonization and resilience initiatives) drive energy storage value and deployments. As a result, continued updates to cost-benefit analysis methodologies, toolsets, and case studies are needed to inform decision-making for planning and operation of the bulk power system. This includes use cases such as transmission Non-Wires Solutions (NWS), generation capacity planning, and market and non-market based bulk system operations.

Because of the energy-limited characteristics of energy storage, careful study is required to establish their equivalent capacity contribution for resource planning and NWS. The potential for energy storage to operate as either load or generation provides increased flexible range, often instantaneously, which may provide new or enhanced capabilities to the power systems which have been historically unvalued, such as frequency response and flexible ramping. Additionally, since 2018, FERC Order 841 has required US-based Independent System Operators / Regional Transmission Operators (ISOs/RTOs) to develop new market designs that accommodate the unique capabilities and limitations of energy storage. These still-evolving market designs have the potential to significantly change the participation models and value for energy storage in the future.

The work being done in this program is closely coordinated with and designed to complement the work undertaken in the Bulk Power System Integration of Variable Generation program (P173), Advanced Generation and Bulk Energy Storage (P66), Renewables Technology Status, Cost and Performance - Hydropower (P193D), Energy, Environmental, and Climate Policy Analysis (P201), Transmission Operations (P39), and Transmission Planning (P40).

P94.019: Transmission and Bulk Energy Storage Technologies and Products

Deployment of variable renewable generation is introducing new bulk power system management challenges which may be addressed by energy storage. Lithium ion battery storage has rapidly emerged in recent years as a transmission-level solution, primarily supporting peak capacity needs of the transmission and generation systems. The costs of lithium ion are expected to continue falling throughout the next decade, but it is possible that lower cost structure energy storage will be needed to enable decarbonization and high renewable energy goals set by many states and jurisdictions.

There is a continuing need to evaluate the durability, cost, safety, and value of lithium ion energy storage technologies, and to continuously evaluate emerging non-lithium technologies which may address issues with current lithium ion batteries. The performance, reliability, and lifecycle economics of these battery storage systems have not yet been demonstrated with long-term track record, and the technologies continue to evolve quickly.

Other, non-battery storage technologies may also play a role in the future if they achieve cost and performance breakthroughs. These may include compressed air energy storage (CAES), thermal storage, electromechanical storage, flow batteries, hydrogen, and others. Some of these technologies are at, or near, pilot-scale demonstration on the grid, while others are at earlier technology readiness levels. In addition, pumped hydro storage remains the large-scale incumbent energy storage technology, with potential opportunities for retrofit of existing plants. As certain technologies advance to pilot projects, and technology announcements continually highlight research developments, continuous critical review of the maturity and demonstration status of these different bulk storage technologies is needed.

This project examines the questions of the performance, cost, safety, durability, functional capabilities, and development timeline of select bulk storage technologies.

P94.020: Transmission and Bulk Energy Storage Modeling for Planning and Operations

The bulk power system has historically been planned to manage peak power flows and minimize cost of generation with a portfolio of conventional generation and "wires" alternatives. Renewable energy deployments and future goals are driving needs for enhanced bulk system planning and operations approaches to ensure sufficient flexibility as well. The emergence of energy storage and distributed energy resources requires new modeling approaches to accurately model all resources, their technical impacts on the power system, and the associated economics.

To incorporate energy storage effectively in bulk resource planning and operations, energy storage needs to be compared on a consistent technical and economic basis with conventional alternatives. This requires the development of new methodologies and modeling toolsets to address the following:

- Capacity planning for new generation (5-15 years in the future)
- Long-term capacity planning to evaluate resource planning in the context of long-term decarbonization and other policies (15+ years in the future)
- Transmission planning and Non-Wires Solutions (NWS)
- Operational controls for energy storage in market and non-market participation models

PS94E: Customer Energy Storage

This project set addresses research questions pertaining to energy storage located at a site furnished by a utility end customer, which may be from the residential, commercial, or industrial segment. These storage systems are typically connected on the customer side of the meter (behind the meter), but they may also be connected to the utility side of the meter (front of meter). Ownership and control models are diverse. They may be owned and controlled by the electricity customer, utility, or a third party, or some combination of these.

Customer energy storage is rapidly evolving, due to the rise in solar PV penetration, addition of load growth (e.g. EV's), decline of battery costs, introduction of new integrated products, and the evolution of new value propositions. The emergence of time-of-use rate structures and new utility customer programs are providing signals to end customers that electricity costs vary through time, and that flexibility also provides value. Natural disasters, such as wildfires, storms, and other phenomena, have permeated the public consciousness with increased concern for electricity reliability. Local generation, coupled with energy storage, has the potential to provide emission-free backup power for customer and community resilience. Additionally, advancements in communications, control, and programmatic advancements provide new opportunities for utilities and customers to collaborate for mutual value that supports customer, power system, and societal objectives.

Due to this rapid evolution in both the commercial and technology landscape, it is important to develop methods and tools for understanding the economics and impacts of customer-sited energy storage. This research area informs the development of innovative programs with societal value and may help to better predict customer behavior in the adoption, sizing, and use of energy storage products. Value propositions for customers can shift rapidly, based on retail energy tariffs, incentive structures, and non-monetary factors. In cases where systems are adopted by customers, there may be intended or unintended impacts to the power system. Methodologies and tools that aid in predicting customer adoption and use of energy storage may support a reliable and affordable electric power system. Innovative approaches to control these devices, may enable significant value for both the individual customer and grid objectives. Additionally, there are practical integration and safety questions to consider with the deployment of customer energy storage. These are especially important for energy storage located in homes and businesses, where the risks of injury or to property are increased. This project works to understand and advance the safety, reliability, economics, and environmental responsibility of energy storage located on customer premises.

This project set covers research related to customer-sited energy storage technical impacts, economics, technologies, and integration issues. Areas of focus include technology evaluation, value modeling, performance analytics, system standards and the advancement of implementation practices.

The work in this project set is performed in close coordination with Program 18 - Electric Transportation, Program 170 - Energy Efficiency and Demand Response, Program 204 - Buildings, and Program 182 - Understanding Electric Utility Customers, Program 174 - Integration of Distributed Energy Resources, Program 200 - Distribution Operations and Planning, and Program 197B / P94H - Environmental Aspects of Energy Storage.

P94.021 Customer-Sited Energy Storage Integrated Products and Projects

Customer-sited energy storage has seen a strong increase in interest over the past five years, with a significant uptake in global market adoption, driven by competitively prices solutions available with a greater degree of demonstrated functionality. Increasingly, policy incentives and innovative utility programs and rate structures are altering the case for end customers. Depending on the scenario, options are beginning to make economic sense to customers in an increasing number of cases. This creates both opportunities and challenges. For example, these new storage resources could be harnessed to enhance customer reliability and resilience while lowering electric bills. However, the adoption of energy storage by end customers is still difficult to predict, and the ability to integrate these resources into power system operations in a safe, reliable, and effective way is still evolving. Therefore, it is still an open question under which conditions these resources contribute positively to the power system, technically and economically. Additionally, electricians, utility field personnel, firefighters, and the public have limited experience with energy storage, so safety and reliability of these systems are an important open issue.

This project seeks to understand the current experiences with energy storage products and project implementations and how well they perform relative to expectations and in the context of the application requirements. It also seeks to understand the experiences of real-world implementation and identify gaps for technical and economic viability, including any issues with safety and reliability, as well as integration equipment (e.g. thermal management, metering, telemetry) and soft costs which significantly impact lifecycle economics. The project also expects to analyze experience with innovative new solutions that couple energy storage with appliances, integrated solar and storage, electric vehicles, integrated building controls and advanced demand management, thermal storage, and other approaches that leverage the creativity of the consumer electronics sector. These systems may also support utility planning and operations. In certain circumstances, customer-sited energy storage could be controlled, either directly or indirectly, by the electric utility. As a result, it is important to understand the capabilities and real-world performance of energy storage systems, controls and communications to operate in modes that are beneficial to objectives for a safe and reliable grid.

P94.022: Customer-Sited Energy Storage Modeling and Analysis

Customer-sited energy storage has the potential to provide value to adopting customers as well as the electric power system, through greater customer reliability, improved peak load management, and improved utilization and integration of renewable energy. However, this value can be difficult to assess and quantify, and customer behavior may be difficult to predict, which provides challenges to the planning and operation of the power system. These gaps may be filled through the development of advanced modeling methods and tools to understand costs and benefits from multiple stakeholder perspectives. Such methods may be used to inform the development of beneficial programs to engage customers to adopt and use energy storage technologies in ways that provides value to the adopting customer, to other customers via value to the broader power system, and to society through improved resilience, load management (e.g. as exhibited by new load growth via EVs) and expanded use of renewable energy.

PS94G: Distributed Generation and Microgrids

Distributed generation (DG) and microgrids are of special interest to electricity customers as well as grid planners and operators, as they have the potential to provide electricity reliability and resilience for critical loads at the edge of the grid during contingencies. They may also support other goals, such as integration of renewable energy and economic objectives. Improvements in underlying technologies and available solutions, as well as declining costs, have made these solutions more attractive. These devices have potential to provide value to both individual customers and to the grid.

This project set evaluates new technological developments to advance the integration and beneficial use of microgrids and of fueled distributed generation. It investigates the following:

- Methodologies and analysis tools for evaluating microgrid and DG costs and benefits, including the quantification of reliability and resilience service benefits.
- Use cases, tools, and methodologies for utility planners to assess a microgrid or DG solution as an alternative or complement to conventional solutions for increased resilience.
- Investigations of fueled distributed generation technologies, such as combustion turbines, microturbines, reciprocating engines, and fuel cells, including combined heat and power (CHP) applications.
- Case studies of DG deployment, integration, and operations to determine gaps, lessons learned, and best practices.

The work being done in this project set is closely coordinated with and designed to complement the work undertaken in the Integration of Distributed Energy Resource (P174) program and Advanced Generation and Bulk Energy Storage (P66) Reciprocating Internal Combustion Engine (RICE) research.

P94.023: Fueled Distributed Generation Technologies, Use Cases, and Integration

Fueled distributed generation (DG) is an important and diverse group of technologies which can provide reliability and resilience service benefits to both utilities and customers. Fueled DG technologies include combustion turbines, microturbines, reciprocating engines, and fuel cells. Some fueled DG have fuel flexibility and can be powered by natural gas, diesel, or other fuels. In recent years, an additional focus on resiliency has increased interest in microgrids, which often requires DG for technical and economic feasibility. In addition to generating reliable base load, fueled DG can provide combined heat and power (CHP) applications for some commercial and industrial loads, meeting thermal loads with onsite capabilities. Other trends, such as the move toward the Integrated Grid, flexible operation, optimization of power system planning, and new customer engagement models, present opportunities and value of distributed energy resources (DER), including fueled DG.

This project investigates the opportunities and gaps for feasible and economic DG deployment and operations. This includes cost and benefit analyses of power system and customer benefits, including benefits from improved reliability and resilience for customer-sited systems. This project will evaluate and monitor existing and emerging technologies, and it will investigate integration considerations through extraction of project lessons learned. The project will also investigate shared value opportunities between customers and utilities.

The key research questions for this project include:

- What resiliency benefits and reliability enhancements may be provided by DG for utilities and customers, and how are they quantified?
- What are best practices for implementation of fueled DG technologies, as standalone systems, in conjunction with other DER, or in a microgrid? These may include siting and integration, technology selection, system configuration, and operations and maintenance (O&M).
- What is the current state and innovation in fuel cells and other emerging or early stage technologies, and what are their intended commercial applications?
- What technical attributes are important to incorporate in models to evaluate costs and benefits of DG and potential hybrid DG projects in different applications and scenarios, including those with mixed generation portfolios of DERs and DGs, serving both thermal and electric loads?

P94.024: Microgrid Technologies, Use Cases, and Integration

Microgrids are clusters of generation, customer loads, and other resources that usually operate connected to the grid, but they can electrically isolate from the utility grid to provide local electric service during contingencies. They are often implemented to support critical customer loads, particularly for public health, safety, and national security institutions. With coordinated planning and control, these technologies may also support power system resiliency and reliability. Microgrids and their components may facilitate integration of localized concentrations of renewable energy, which can be balanced against local loads and stored to minimize the overall impacts on the distribution network. Microgrids may provide services to the grid in the form of generation capacity, bulk electricity operations, T&D peak load management, local voltage control, and enhancements to resiliency, when they are integrated with grid planning, control systems, and operational practice.

The technical and economic feasibility of microgrids is typically built around the attainment of specific customer or grid objectives with a location-specific set of available resources. As a result, it may be determined only by conducting appropriate local screening and site-specific assessments. This project aims to advance and apply methods to analyze and understand reliability and improvements in resilience services, feasible configurations, optimal DER mix, and behind-the-meter (BTM) interconnection findings from deployed microgrid projects. Site-specific energy economics, grid constraints, environmental constraints, and control strategies are also important aspects to consider in the evaluation of feasibility and design of microgrids. Research is needed to determine the conditions under which microgrids are feasible, and how they might be implemented with maximum benefit and minimum risk.

PS94H: Environmental Aspects of Energy Storage

This project set is cross-listed as Project Set 197B in the Environment research sector. The rapidly changing electric power system is leading to increased proliferation of a diverse range of energy storage technologies for maintaining grid flexibility and providing ancillary services. However, due to emerging and evolving storage technologies, applications and markets, our understanding of the potential environmental, public and occupational health, and end-of-life risks is still rapidly developing. This poses the following challenges:

- Diverse Regulatory Considerations: These technologies are likely to be subject to a combination of divergent, evolving and data-limited federal, state, and local environmental regulations on permitting or siting issues, worker safety concerns, public health and risk assessments, and equipment decommissioning/disposal, among others.
- Worker, First Responder, and Public Safety: Energy storage installations may increase safety risks for utility workers, first responders, and the public if the devices are not properly connected, maintained, and handled during emergencies.

The objectives of this project set are to address health, safety, and electromagnetic field (EMF) aspects and end-of-life (EOL) management; as well as modeling and assessments of relevant environmental issues for energy storage. The storage technologies to be investigated include, but are not limited to, batteries (including flow battery designs), flywheels, thermal storage, and compressed air energy storage. The deployment scales considered include transmission and distribution scales on the grid, behind-the-meter (BTM) installations, or in electric vehicles (EVs). The research helps utilities, the storage industry, and other interested stakeholders address numerous interconnected issues by:

- Advancing Health and Safety Knowledge and Practices: Conducts research on emerging environmental, human health, electromagnetic and radio frequency (EMF and RF), and utility worker and public safety issues to support proactive risk management of these technologies. Particular focus is on fire safety and impacts from emergency events.
- Understanding Lifecycle Environmental Impacts of Different Technologies: Assesses the importance of environmental aspects of these technologies from resource extraction, through manufacturing, transportation, and use, to final disposition.

- Informing Regulation and Educating the Public: Places the relevant potential environmental benefits and challenges into a broader context relevant to utilities, non-utility DER owners and operators, the storage industry, regulators, and the public.

This project set consolidates in one integrated research effort the environmental, human health, and safety benefits and challenges of a broad range of emerging storage technologies, applications, markets, policies and regulations. EPRI"s environmental, human health and safety expertise will combine with the expert technology, codes and standards, technology implementation and existing safety resources in the energy storage program (Program 94). Other programs that will collaborate include Program 18 - Electric Transportation; Program 60 - Electric and Magnetic Fields and Radio Frequency Health Assessment and Safety; Program 62 - Occupational Health and Safety; Program 203- Air Quality and Multimedia Characterization, Assessment and Health; the RICE Interest Group and Natural Gas Interest Group; and Program 192 - Environmental Aspects of Renewables. This project set also collates the activities and perspectives of a broad range of stakeholders, forming a collaborative network that helps ensure consideration of all relevant issues, complexities, and potential solutions. The Energy Storage Integration Council (ESIC), developed and convened by Program 94, will be a substantial collaborative asset that can reach 2000 technically-oriented stakeholders in the energy storage industry. Specific project set goals and activities include:

- Resolving critical knowledge gaps related to EOL management of electrochemical batteries. The research efforts will be designed to:
  - Improve understanding of the environmental, financial and logistical aspects of battery recycling as compared to disposal; and
  - Assess reuse, repurposing, and remanufacturing options to support corporate risk and waste management strategies and revenue opportunities.
- Conducting modeling and assessments to fully evaluate the environmental footprint of energy storage systems. The research efforts will be designed to:
  - Track, inform, and develop environmental aspects of storage siting and permitting activities, as well as best management practices on issues such as spill prevention, fire safety, and emergency response safety; and
  - Investigate changes to regional greenhouse gas (GHG) or air emissions as a result of incorporating grid-scale storage with varying operational cycles to the electricity network.
  - Addressing potential human health and safety effects of increased deployment of energy storage at the public or community level, and within occupational settings. The research efforts will be designed to:
    - Clarify potential public health risks during normal operations or emergencies
    - Provide an effective safety environment for workers and first responders during emergency incidents such as fires

This project set contains three projects:

- Environmental Aspects of Energy Storage End-of-Life
- Health, Safety, and EMF Aspects of Energy Storage
- Environmental Modeling and Assessments for Energy Storage

SUPPLEMENTAL PROJECTS

- Battery Energy Storage Fire Prevention and Mitigation: Phase 1
- Customer-Sited Energy Storage Field Testing
- Emerging Energy Storage Technology Testing and Demonstration
- Energy Storage Analysis: Finding, Designing, and Operating Projects
- Energy Storage Controls for Optimized Performance
- Energy Storage Implementation Practices: Building Organizational Capability for Deployment
- Energy Storage Performance and Reliability Data Initiative
- Energy Storage Technology Update
- Energy Storage Test Protocol Development
- Fueled Distributed Generation: Evaluation and Lab Testing of Emerging Systems
- Utilizing DER for Advanced Distribution Resiliency
- Valuation of Hydrogen Technology on the Electric Grid Using Production Cost Modeling

174 - DER Integration

Program Description

This program addresses utility industry technical and economic challenges to integrate distributed solar, battery storage, and other distributed energy resources (DER). Managing and screening interconnection requests, modeling and analyzing grid impacts, specifying grid-support functions and settings, and applying monitoring and control systems are relatively new activities and require new learning for most utilities. Effective integration of DER needs to be considered in all aspects of distribution planning, operation, protection coordination, voltage regulation, power quality and safety. Hosting DER also brings new economic challenges and tradeoffs for providing reliable service with increasing deployment levels. Business risks and opportunities need to be evaluated.

Research Value

The knowledge acquired through this research program will support members to:

- Analyze DER integration issues and make decisions about levels, settings and types of DER
- Manage interconnection queues and identify effective screening methods
- Track, document, and address grid issues caused by rising DER levels
- Determine requirements and take advantage of evolving standards for DER interconnection
- Train staff on integration technology (smart inverters, grid edge devices, control systems etc.)
- Develop strategies for managing and integrating customer-sited DER
- Assess both technical and economic aspects of DER integration with existing distribution assets
- Use data analytics for assessment and insight into DER operation cost and benefit

- Prepare existing and future distribution grids for more effective integration

Approach

The research is aimed to provide practical tools, resources, and guides that can be applied in day-to-day processes. The nature of projects includes computer modeling, lab testing, field evaluation, software development, data analytics, industry surveys, standards support and working group facilitation. All projects aim to provide industry leadership and build on previous work related to DER integration. Deliverables include tools, software, algorithms, technical reports, whitepapers, webcasts and training courses.

DER business practices, strategy and cost-benefit analysis are key elements, including assessment of non-wires alternatives and optimizing PV operation with storage and controllable loads. Tools such as DRIVE (Distribution Resource Integration and Value Estimator), PVAT (PV Adoption Tool), DERMS Testbed and smart inverter simulators are developed through this program.

There are five project sets supporting DER integration. Each address specific research efforts and deliverables:

- Grid Impact Analysis
- Smart Inverters and Devices
- DERMS and Microgrid Controls
- Practices, Programs, and Economics
- Technology Transfer and Industry Coordination

Accomplishments

The Integration of DER program has delivered valuable information to members and industry. Examples of recent program outcomes:

- Industry leadership to define and evaluate smart inverters, (3002008218), this work continues to investigate performance with various grid support functions, voltage and frequency ride thru, islanding detection, and regulation impacts with variable solar irradiance and grid conditions.
- The Distribution Resource Integration and Value Estimation (DRIVE) tool. This software tool allows utilities to perform hosting capacity analysis and determine distribution impacts of DER in their planning tools (3002008297).
- An Integrated Grid Benefit-Cost Framework that provides a systematic approach for analysis of microgrids. This report, published in 2017, enables consistent CBA methodology with other grid options. (3002010288).
- Innovative research using smart inverters to actively manage real power output. A foundational report examines the economic and regulatory issues associated with utility curtailment and provides a roadmap for considering scenario-driven outcomes (3002010289).
- Technical support to major updates in IEEE P1547 which led to successful balloting and release in 2018. EPRI continues a major effort to support members in navigating the new standard; updating interconnection requirements and processes; and coordinating the major

changes with distribution automation, DER grid support options and new DER management systems (DERMS).

Key Activities

In 2020, this program expects to accomplish the following:

- Produce training, workshops, webinars, and discussion forums on current integration topics.
- Conduct interest and user groups, laboratory and field evaluations, and demonstrations of DER management and monitoring that promote hands-on knowledge and experience sharing
- Provide methods for choosing smart inverter settings and optimized operation of DER for grid-support, including research of adaptive, learning inverter settings
- Investigate application of technologies to improve control in the larger grid or a microgrid, and accommodate higher penetrations of distributed energy resources
- Develop a comprehensive understanding of DER during abnormal and transient conditions, including anti-islanding and fault characterization to support PQ, protection system design and grid stability
- Simplify the DER interconnection application and screening processes, providing methods to automate where appropriate and streamline for more efficient and effective evaluations
- Define and document comprehensive DERMS requirements and end-to-end integration methods, develop DERMS test bed with control strategy evaluation capabilities
- Address the challenges and complexities of active power management of DER, including methods for more flexible interconnection options and capability to estimate plant productivity vs. scale
- Develop and maintain mechanisms for technology transfer to keep members up to date on integration issues, standards activities, technology advancements, and new challenges

Estimated 2020 Program Funding $5.5M

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PS174A: Grid Impact Analysis of DER

This research examines ways to benefit from autonomous and managed functionalities of DER without sacrificing safety, reliability, or effectiveness. As DER penetrations increase, it is important for distribution operators and planners to fully understand DER impacts and capabilities to maintain and/or improve overall customer service while maximizing asset utilization. With this in mind, the project set is focused on the development of methods and guidelines to assess a wide range of DER considerations from determining the best functions and settings to quantifying the technical impacts of managed DER through advanced control, such as DERMS. In addition, it aims to advance the state of the industry by evaluating new managed and autonomous functions that address both short-term and steady state distribution system issues. Finally, the project set seeks to quantify the technical benefits associated with different strategies for the grouping/aggregation of DER to achieve an overall distribution system objective.

P174.001: Grid Impact Analysis of DER

This project set provides engineers with methods and guidance for operating and planning with a wide range of DER penetration levels. DER modeling and simulation is essential to understand and predict the effects of DER in various grid conditions. Key research questions are: what is the best way to determine how much DER my systems can accommodate, how can I use hosting capacity analysis to my benefit, how can I advance my hosting analysis to address planned integration methods, how is hosting capacity affected by DER grid-supportive functions, what are the best DER functions and settings to use, will devices acting autonomously interfere with one another or other distribution assets, how can managed control of DER, such as DERMS, help to meet my utility goals, and how can DER be coordinated with traditional equipment (line voltage regulators, load tap changers, capacitor banks, etc.) to achieve an objective. This project set addresses these questions and provides insights to grid impacts, potential benefits and how to accommodate more DER.

PS174B: Smart Inverters and Grid Supportive Technologies

To address the challenges of increasing penetration of DER, there is a need to better understand the operation and behavior of diverse DER technologies including solar PV, energy storage, PV plus energy storage, and controllable loads. This project set evaluates these technologies so that their limitations are known and their full potential can be identified and utilized for maximum benefit. Test results help to model these technologies more accurately in power system analysis tools. This project set also aims to advance the state of grid-supportive DER by leveraging learnings from field experiences and by providing industry leadership to define the next level of smart inverter functions.

P174.003: Smart Inverters and Grid Supportive Technologies

This project set addresses questions related to solar photovoltaic (PV) and energy storage smart inverters as well as other grid supportive technologies, such as voltage regulation devices deployed at the edge-of-the-grid. Example research questions include those regarding smart inverter function behaviors, their interaction with one another, the accuracy and effectiveness of functions, and their potential effect on the risk of unintentional islanding. Other questions include those related to the integration of energy storage with PV, the dynamic characteristics of individual inverters and plants, evaluation of device features specified in interconnection standards (e.g. IEEE 1547-2018, CA Rule 21, HA 14H), connect-ability and interoperability, and data analytics.

PS174C: DERMS and Microgrid Integration

This project set is focused on supporting DERMS strategy, architecture, procurement, integration and operation. It provides up-to-date information that informs of technology capabilities, breakthroughs and lessons-learned from DERMS projects worldwide. In addition, the project set provides tools and test procedures to carry out independent evaluations of DERMS. It also conducts research addressing microgrid implementation challenges, including identifying various system design approaches, evaluating operational control schemes, determining technical requirements, and supporting request-for-proposals.

P174.011: DERMS Requirements and Functional Specifications

It is becoming increasingly necessary to monitor and manage DER to maintain grid efficiency, reliability and power quality as quantities of DER increase. DER Management Systems (DERMS) are the communication and control systems that serve this function. These systems are new to the utility industry and are available in diverse forms, including utility DERMS, home/facility Energy Management Systems, aggregator fleet controllers, and microgrid controllers. There are many questions surrounding DERMS functionality, performance, interfaces, and integration with overall distribution and bulk system operations. This project set is addressing these gaps, defining and aligning DERMS functionality, accelerating product availability and assessing emerging systems. This project set helps utilities determine the value proposition of DERMS, identifying requirements and specifications, and conducting laboratory testing and field demonstrations to recognize incremental value streams and benefits of the technology.

PS174D: Practices, Programs and Economics

The aim of this project set is to improve the operational efficiency by which utilities manage DERs on distribution and inform related utility strategic planning rationales. Activities seek to, for example, streamline utility interconnection practices and procedures in ways that reduce costs while maintaining grid safety and reliability; provide guidance regarding the economic implications of scenario-based DER integration approaches - including those specific to advanced inverter functions under different DER rate structures; qualify utility DER business models, programs, and procedures, including those governing non-wires alternatives projects; and notify DER adoption forecasting methods that can inform distribution planning activities.

P174.008: Practices, Programs and Economics

The presence of widespread DERs impacts a range of fundamental utility operational and business processes that have high visibility to customers, governments, and regulatory bodies. How can these processes be evolved and updated? Likewise, DERs have economic implications for customers, electric utilities, and society, but they are not yet fully understood due, in part, to changing standards and market rules, as well as technology advances. What DER grid integration tactics, associated business model approaches, cost-benefit analyses, and adoption forecasting methods are required to notify effective utility strategic planning and decision-making objectives?

PS174E: Technology Transfer and Industry Engagement

This project set delivers practical DER integration knowledge and enable members to share experiences, issues, and solutions related to DER. Utility managers and staff can immediately use the knowledge provided via technical transfer to improve distribution system design, screening, troubleshooting, and safety practices.

Technology Transfer and Industry Engagement

The Technology Transfer and Industry Engagement project set provides members with a broad overview of current issues, activities and learnings related to DER integration. Tech transfer resources are designed to keep members up to date on the rapidly developing technologies and standards. They support utility staff and decisions related to DER strategy, planning, operation, management, and the application of field experience. Typical research questions addressed are:

- What are current trends in DER deployment, interconnection application processing and technical review, and screening practices?
- Are there typical DER integration-related problems where solutions can be shared and enhanced?
- What standards and practices need to be considered for higher penetration and grid support from DER?
- Will utility customer and related distribution power quality concerns change with DER?
- What is needed for DER"s built-in protection and control responses to be sufficient and coordinated?
- Given a wide range of DER integration experiences among members, what lessons-learned and new practices can be shared and applied?

SUPPLEMENTAL PROJECTS

- Distribution Resource Integration and Value Estimation Tool User Group
- Educating a Digital Power Workforce to Be GREAT with Data (GridEd Membership)
- Evaluation of Inverter On-Board Detection Methods to Prevent Unintended Islanding
- Field Validation Tool for Smart Inverter Configuration and Settings
- GridEd Training Courses and Activities
- Inverter-Based DER Dynamic Response Characterization for Protection, Planning, and Power Quality
- Low-Cost, Secure DER Network Gateways for Control Integration of Smart Inverters
- Navigating DER Interconnection Standards and Practices
- Utilizing DER for Advanced Distribution Resiliency

180 - Distribution Systems

Program Description

The Distribution Systems research program addresses the challenges facing distribution asset owners and operators. This program is focused on distribution assets, their life cycles, and industry issues.

Research addressing the asset life cycle is designed to improve utilities' ability to acquire, operate, maintain, and dispose of distribution assets. This research can produce results impacting specifications, inspection tools, maintenance practices, fleet management, and other key aspects of distribution owners" responsibilities. Examples of assets covered in this program are wood poles, transformers, reclosers, cable terminations, and overhead conductor. Examples of industry issues explored are the use of reliability metrics, fleet management approaches, safety, and resiliency.

Research Value

This research program focuses on distribution system assets and their specification, operations, maintenance, and disposal. The results from this program should help asset owners do the following:

- Enhance safety, both for utility workers and the public
- Improve specifications for new assets
- Develop maintenance practices based on a technical basis
- Reduce maintenance costs
- Proactively plan capital and maintenance budgets
- Increase distribution system resiliency
- Improve asset and system reliability

Approach

This program produces advanced knowledge, technologies, and tools to inform decisions regarding the distribution asset's life cycle. Researchers produce these results by identifying high-value research opportunities, creating and executing robust research projects, and facilitating effective technology transfer of the results to utilities. Researchers use various approaches to produce these results, including:

- Laboratory testing of new, aged, and failed equipment
- Evaluation of emerging technologies
- Investigations into equipment failure modes and degradation mechanisms
- Collection and assessment of utility practices
- Accelerated aging of components
- Assessment of asset performance

EPRI transfers these results to utilities through reports, webcasts, interest groups, task forces, videos, and databases.

There are five projects in this program, each with multiple research tasks. The projects are:

- Overhead Assets
- Underground Assets
- Distribution Automation Assets
- Safety
- Asset and Reliability Analytics

Accomplishments

The following are some of the many valuable research results that the Distribution Systems program has delivered in the past:

- Sensor performance testing results. Laboratory testing of line sensors provided data that utilities can use to enhance specifications.
- Development of pole sensors. Development and field tests of sensors to detect pole angle and condition in real time.
- Understanding of grounding configurations for vehicles. Laboratory testing of energized trucks informs grounding and safety practices.
- Assessment of resiliency approaches and technologies. Field, laboratory, and computer tools to help utilities understand effectiveness and prioritize resiliency improvement options.
- Collection and curation of industry practices around underground infrastructure. A robust repository of industry practices helps utilities identify areas for improvement of inspection, maintenance, and safety practices.
- Network training. Annual training brings together industry experts to educate utility members on the design, challenges, and approaches unique to the network underground system.
- Investigation of high-impedance faults and mitigation methods. Research into downed conductor and high-impedance faults helps utilities understand the risk and phenomena as well as options to detect downed conductors and mitigate the risk.
- Testing of underground switches. Development of new industry intelligence on switch aging and performance in underground systems.
- Laboratory testing of manhole events and restraint systems. Controlled laboratory testing of manhole events provides real-world performance information of restraint and mitigation systems.

Key Activities

The Distribution Systems research program expects to accomplish the following:

- Test alternative pole and crossarm materials
- Evaluate pole inspection technologies
- Test DGA monitors for network transformers
- Update the Underground Distribution Reference Book with new information on grounding
- Evaluate virtual inspection techniques for distribution automation assets
- Investigate cyber and physical security for distribution automation
- Develop a guide on arc-flash analysis
- Investigate the impacts of 5G cellular equipment on distribution practices
- Develop a framework for asset management analytics
- Test natural language processing for outage record coding

Estimated 2020 Program Funding $5.25M

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P180.001: Overhead Assets

Managers of overhead distribution systems are frequently challenged to improve system performance, manage a fleet of aging assets, and deploy new technology that is expected to perform for decades. Emerging technologies can offer opportunities to improve performance, but utilities lack objective performance assessments. Because total replacement of aged assets is impractical, utilities must strategically plan resources to best maintain system reliability while promoting safety, reliability, and environmental stewardship. The Overhead Assets project investigates new designs and approaches for overhead assets, asset degradation and failure, inspection methods, and emerging technologies to enhance component reliability, longevity, and cost-effectiveness. Asset managers can use the test data generated by the research to make informed decisions about selection, installation, inspection, maintenance, and replacement.

P180.002: Underground Assets

Utility companies that own and operate underground distribution systems face many challenges and changing needs. Installing and maintaining underground infrastructure are complicated by accessibility issues, and much of the early installed infrastructure is reaching the end of its useful life. Utility managers are charged with managing costs, improving system reliability and resiliency, increasing power throughput, and improving the health and safety of workers and the public. Significant changes to electric distribution systems are underway, including new underground equipment and materials, automation systems, and new monitoring technologies. At the same time, many utilities are losing institutional knowledge. In addressing these challenges, the research performed under this project focuses on equipping utilities with the knowledge to acquire, optimize, and maintain underground distribution infrastructure. Key focus areas include emerging inspection methods, new maintenance approaches, asset life extension, and work practices for underground distribution systems. The activities are part of a multi-year research plan to close the existing research gaps.

P180.003: Distribution Automation Assets

Distribution automation (DA) enables remote, real-time monitoring, operation, and optimization of utility distribution systems. DA assets are becoming more common, and the number being deployed is growing. It is important for utilities to actively manage DA assets due to their prevalence and their criticality to grid modernization efforts. The current DA research needs include understanding failure and degradation modes; improved inspection techniques and maintenance procedures; tools and technologies to remotely manage settings and firmware; reference books, asset databases, practices, and guidelines to assist with asset deployment and management; and a collaborative environment for sharing lessons learned and leading practices.

P180.004: Safety

Because electricity distribution involves multiple risks for both the public and utility workers, utilities put in place many risk-reducing procedures and processes. Improvements are always possible; new practices, protective approaches, equipment, tools, and technologies must be assessed carefully to evaluate the impact on worker and public safety. The goal of this research is to evaluate risks, protective approaches, and equipment and to investigate new technologies to improve safety. Research areas include grounding and personnel protection, arc flash, downed conductors, and tools and technologies aimed at improving safety.

P180.005: Asset & Reliability Analytics

Distribution systems are composed of many assets that are distributed over a wide geographic area. Many of these assets are near or past their expected service life. Typically, an individual asset's low cost makes online monitoring difficult to justify, but the cumulative impact of aging equipment can have significant reliability and cost implications. Distribution asset managers are thus faced with the unique challenge of addressing aging infrastructure—and the associated risk—with minimal tools and information to support decision making. Many electric utilities are considering or have implemented asset management programs to minimize equipment life-cycle costs and risks, with much of the effort historically targeted at the more expensive transmission components, such as substation power transformers. These approaches could provide significant value to distribution systems. However, the data, analytical tools, and models required for distribution assets are not well established.

SUPPLEMENTAL PROJECTS

- Distribution Recloser Life-Cycle Management
- Edge-of-Grid Voltage Regulation Device Life-Cycle Management
- Evaluation of Satellite Imagery for Transmission & Distribution Applications
- Finding Live Downed Conductors with AMI
- Improving Grid Safety and Resilience During Extreme Weather Events and Wildfires
- Overhead Distribution Design for Resiliency and Reliability
- UAS Automation Technologies for Transmission Inspection
- Unmanned Aircraft System (UAS) for Utility Operations: Cybersecurity and Hardware Performance Assessment
- Unmanned Aircraft Systems for Storm Response

200 - Distribution Operations and Planning

Program Description

Distribution systems have been designed for one purpose: reliably serve all customers in a safe, reliable, and cost-effective manner. However, in this new era additional objectives must be considered as well, including increasing resiliency and reliability, integrating DER cost-effectively, utilizing DER as non-wires solutions, improving operational efficiency, and potentially using distribution systems to provide bulk system services. Grid modernization efforts are underway throughout the industry to achieve these goals.

Tools and technologies, such as distribution management systems, automation systems, protection systems, and planning tools must adapt to facilitate the needs of this new modern distribution system. New technologies and their integration will be critical to allow distribution planners and operators to meet these goals and truly realize the concept of an "Integrated Grid" where traditional assets work in concert with new technologies and resources to yield a more efficient, reliable, and customer-centric sustainable grid. This creates certain challenges as some of these needs are current and immediate. As such, a more focused effort in the form of a dedicated EPRI program that is focused on assisting utilities in their grid modernization efforts is required.

EPRI's Distribution Operations and Planning Program (P200) is designed specifically to provide members with research and application knowledge to support planning and management of today"s grid as well as tomorrow"s. The Program provides research results that assist utilities in their transition to tomorrow"s distribution system using a balanced, no-regrets approach to grid modernization. Advanced tools for planners, operators, and analysis experts are central to these efforts.

This program will serve as the hub for all activities related to distribution modernization, focusing on:

- Developing and implementing new planning processes and tools that target grid modernization, balancing reliability, cost and risks
- Developing and implementing new, advanced operation and control schemes that maximize use of existing and new technologies
- Improving visibility (situational awareness) through new methods and technologies for cost-effective metering
- Developing adaptive and scalable protection solutions for active distribution systems
- Developing new and innovative distribution automation schemes that improve reliability
- Advancing workforce skill development through new training activities and tools
- Sharing new learnings from industry-wide grid modernization efforts.

Members of the Program gain access to a portfolio of projects that cover the range of distribution issues, as well as the opportunity to collaborate with other members and EPRI technical experts to share ideas and solutions, improve knowledge transfer, and ultimately improve safety, reliability, and operational performance.

Research Value

The mission of EPRI's Distribution Operations and Planning research program is to assist utilities in their grid modernization efforts, helping them optimize the use of existing assets while simultaneously maximizing benefits of new technologies and resources to yield a more efficient, reliable, and customer-centric sustainable grid. The research within this program is intended to equip distribution planners and operators with the means necessary to overcome the challenges of today while attaining the desired modern grid of the future. This includes the supporting and development of new planning processes and frameworks, models, tools, reliability assessment analytics, as well as incorporation of new automation, protection, and control technologies that will be required to transform the current distribution system into an active distribution system that integrates and uses new distributed technologies and resources.

With the knowledge acquired through this research program, members will gain access to information that can help them accomplish the following:

1. Plan and operate a changing, integrated distribution system;

2. Enable planners to take advantage of new analysis methods within their existing planning tools (e.g., hosting capacity methodology, advanced distribution automation and control, etc.)
3. Support the implementation of advanced distribution observability and control for reliability improvement, voltage control, and the dynamic grid management;
4. Assess and vet the costs and benefits of smart grid applications and advanced technologies; and

Leverage industry-leading practices in the management and operation of modern distribution systems.

Approach

EPRI's Distribution Operations and Planning research program conducts research projects that lead to methods and tools used by system planners and operators responding to the challenges of modernizing the distribution system. The program conducts research projects that lead to prototype methods and tools that are applied and validated by system operators before being transferred to commercial vendors that supply and support member applications. EPRI also engages with external industry standards, regulatory, and research efforts to ensure that the EPRI research program is taking advantage of broader industry efforts and advancing the state of the art.

The research in the Distribution Operations and Planning Program addresses four primary areas:

1. Advancement of distribution planning practices, methods, and tools
2. Advancement and incorporation of new approaches for modernizing grid operations
3. Identification and application of new protection techniques for improved grid resiliency
4. Advancement of modeling and simulation approaches that enable new technologies and resources to effectively be captured in planning and operational tools.

This research program also strives to provide members near-term, mid-term, and long-term value each year. This is accomplished through close collaboration and feedback from utility advisors and task force members.

This program is designed for close coordination with the work in other research areas, particularly Integration of Distributed Energy Resources (P174), Distribution Systems (P180), Transmission Operations (P39) and Transmission Planning (P40), Energy Storage and Distributed Generation (P94), Information and Communication Technology (P161), Energy Efficiency and Demand Response (P170), Bulk Power System Integration of Variable Generation (P173), Technology Assessment, Market Analysis, and Generation Planning (P178), and Understanding Electric Utility Customers (P182).

Accomplishments

Prior research and findings from this effort has given valuable information that has helped its members and the industry in numerous ways: The following products highlight recent results from these efforts:

- Forecasting for Active Distribution Planning to identify current practices & evaluate future system assessment needs.

- Evaluating requirements and developing methods for automating the assessment of future planning scenarios
- Detection & Protection of Islanded DER to identify characteristics of islanded DER under different gen/load balances, transformer grounding, faults.
- Smart Distribution Applications for DER to demonstrate a new DA/FLISR algorithm that combines DA, VVO, DR to address the loss of DER.
- Evaluation of Single Phase Automated Restoration to identify the benefits & challenges that should be considered when installing single-phase automation.
- Methods and Considerations for Applying Hosting Capacity to provide insights into impact factors and methods, including what matters most and the implications when applying it.
- Investigate future planning practices and process needs for the distribution system of the future
- Summary of the present state of the transmission and distribution industry with respect to alarm processing
- Innovative reliability statistics being deployed across the globe and their impacts on reliability investment, operational and automation decisions
- Development of specifications and requirements for DERMS
- Emerging techniques and applications for utilizing AMI in distribution operations

Key Activities

- Provide guidance to target grid modernization deployments based on desired future state
- Provide planners and control center managers and staff the opportunity to discuss critical issues related to distribution operations and planning, training, and practices through multiple face-to-face workshops.
- Implementation of an online database to facilitate member sharing and benchmarking across the breadth of planning practices and criteria
- Develop decision tools and methods to optimize and reduce economic risks associated with changing resources and planning uncertainties
- Define criteria, metrics, and analytics to quickly identify viable NWA solutions
- Define a curriculum of training and education necessary to properly equip the Distribution System Operator of the Future
- Develop a specific reference for the development of DSCADA and DMS user interfaces
- Develop and execute a collaborative cyber drill workshop on a high impact scenario for distribution operations.
- Provide a tool in CYME and Synergi that performs wide-ranging protection coordination, load-flow, and fault studies to assess protection under different grid conditions
- Examine simple, practical adaptive protection configuration changes that can be activated automatically
- Present existing common protection algorithms and practical techniques that are used to detect and trip distribution-connected generators when they become islanded from the main power system.

- Enhance the DRIVE™ DER Mitigation module to assess the impacts of additional mitigation options that potentially increase a feeder's ability to accommodate DER as well as improve the methodology to be applied system-wide.
- Examine the use of DMS state estimation operational model data to improve planning models
- Improve hosting capacity analytical methods

Estimated 2020 Program Funding $4.0M

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PS200A: Tech Transfer and Industry Collaboration

The work being done in this project set is closely coordinated with and designed to complement the work being done in the Integration of Distributed Energy Resources (P174), Energy Storage and Distributed Generation (P94), and Information and Communication Technology (P161) programs.

P200.001: Technology Transfer and Resources

Distribution companies face a variety of pressures and technical challenges. To address these challenges, utility planners, engineers, and operators need to stay familiar with the latest technologies, software tools, standards, and procedures for optimizing distribution system performance. At the same time, many utilities are losing valuable experience as the aging workforce retires.

PS200B: Planning

Research in this project set will advance the planning tools, methods, and practices needed to realize the modern distribution system. These capabilities are key to ensuring planning departments can continue to effectively and efficiently identify needed system expansions and upgrades considering increasing uncertainties, complex system interactions, and changing system objectives and stakeholder engagement needs. Research spans all facets of planning including forecasting advancements, methods for holistically evaluating non-wires alternatives, and planning practices to address uncertainty.

P200.002: Planning for Active Distribution Systems

Modern planning methods, tools, and practices are needed to account for evolving system characteristics and planning objectives and ensure the system remains safe, reliable, and cost-effective. What are the gaps in existing planning processes and tools? What new analytics can help automate processes to better utilize valuable engineering time? How does distribution planning fit in with Integrated Resource Plans and how can DER be properly accounted for as a potential non-wires alternative? These are some of the key research questions being addressed in this project.

PS200C: Operations

This project set focuses on developing and demonstrating new technologies, tools, techniques and training methods to enable DCC managers and professionals to meet the challenges of today and tomorrow, while improving their ability to offer safe, reliable and efficient electric distribution service to their customers.

This project set will produce results in the form of reports, guidebooks, training, and tools that equip DCC managers and professionals can immediately implement or include in upcoming system upgrades or enhancements to meet the pending challenges head on.

P200.003: Operations and Control for Modern Distribution Systems

Significant changes are on the horizon within the distribution control center. With the expanding presence of distributed energy resources, and the rapid deployment of grid modernization technologies, the distribution control center (DCC) is experiencing a dramatic increase in complexity. These changes cover a wide range of topics, including: training new system operators, cyber security, situational awareness, operations with distributed energy resources, and incorporation of grid modernization technologies.

What new roles and responsibilities will the operator need to fill in this new environment? How can distribution management systems advance to leverage new technologies and energy resources? How can new sensing and automation solutions be justified for investment and targeted for deployment? How can operations better prepare for cyber threats and severe weather events? What does operations need to do to prepare for potential distribution-based markets? These are just a few of the questions that are being addressed in this project.

PS200D: Protection

This project will focus on the development of new methods for protecting the modern distribution grid and to take advantage of the new capabilities made available through grid modernization. These new methods must take into account the effects of widespread distributed generation and advanced control schemes on the distribution feeder. Distribution protection engineers will use the methods and protocols developed through this project to evaluate distribution protection schemes and philosophies, including the impacts of energy-efficiency and demand response programs and technologies.

P200.006: Protecting the Modern Distribution Grid

The optimal performance of protection relays is critical to the safe, reliable and stable operation of modern power systems. When a disturbance occurs on a power system the protection systems should act in concert to quickly isolate the faulted equipment, while minimizing customer outages and impact on power quality.

The key research question of this work is to establish practical solutions for how protection systems can be assessed, designed, and implemented for solving modern grid challenges. These challenges include developing resilient protection systems considering integration of distributed energy resources, unintentional islanding of DER, improving protection sensitivity, and designing protection with variable short circuit levels and changing system topologies.

PS200E: Analytics for Operations and Planning

This project set provides engineers with the analytics necessary to modernize how existing assets and new resources are modeled and simulated for grid analysis. As new technologies are integrated into the grid, both planning and operational models and solutions need to evolve in order to properly capture the effect of these resources. Additionally, modeling of existing resources connected to distribution need to evolve as well to more effectively achieve the goal of a digitized electric grid.

P200.007: Advanced Methods for Modeling Distribution Resources

Advanced analytical solutions that can support, and bridge across, operations and planning are needed. Distribution engineers are evermore relying on modeling for operations and planning and the vast amount of data being collected within the distribution system is ever-growing.

How do distribution engineers address the interwoven issues across planning, operation, and protection where big data, new resources, and new system conditions are emerging? How can distribution engineers turn the vast amount of data available into actionable information? How can critical distribution systems be modeled better, providing as-needed up-to-date information for planning and operations? How can advanced analytics such as hosting capacity be further improved to better inform future investment decisions for DER? These are just a few of the research questions being addressed in this project set.

SUPPLEMENTAL PROJECTS

- Distribution Resource Integration and Value Estimation Tool User Group
- Distribution System State Estimation Test
- Finding Live Downed Conductors with AMI
- Improving Distribution Control Center Situational Awareness with New Alarm Management Philosophies and Rationalizations
- Integrating AMI into Distribution Operations
- Inverter-Based DER Dynamic Response Characterization for Protection, Planning, and Power Quality
- Modernizing a Distribution Control Center
- Modernizing Distribution Planning Using Automated Processes and Tools
- Optimal Distribution Automation Switch Placement

Project Synopsis – Underutilized Technologies / Other Ideas

New Tower Designs - New transmission tower designs - ex Transource They also presented their design a few years go to National Grid. Below were some initial observations back then; The structures have a wider footprint and therefore requires a larger ROW Width, which we rarely have. They show the phases being a 4ft wider than "typical". the EMF comparison to typical double circuit with phasing of A-B-C/A-B-C but we would typically look to configure A-B-C/C-B-A to reduce EMF. I don't doubt the EMF is lower with a delta but it'd be interesting to see if you really achieved much benefit on EMF compared to typical A-B-C/C-B-A configuration. This design is not live line compatible. Overall, we recall that the cost of using their design was extremely high.

New Composite Conductors -

Renewable Fuel Generation /Storage -

Advanced or Small Modular Nuclear – This could be in the form of what's presently being built at the Vogtle (GA) or Hinckley Point (UK) stations, which is pretty standard, or in the form of small modular reactors, which could be running by 2030, or even load-following nuclear plants, which require a bit more development, but would perfectly complement renewable generation without producing the GHG emissions of the gas plants. From what I see on the NYISO site for the average state load, it looks like the State could use about 10GW of new nuclear (3 – Hinckley Point C plants, or 5 – Vogtle 3&4 plants) with another 2000MW of load following nuclear. That might likely achieve the 70x30 goals by itself. So, in short, I think we should be looking at advanced nuclear generation technologies as a true GHG-free solution (and if you compare nuclear to wind+storage for guaranteed generation, nuclear beats wind+storage in cost by about 5:1).

Large Dispatchable Loads – If you take a look at some of the preliminary results from the recent NYISO 70x30 CARIS study you will see that for certain scenarios, there is substantial predicted wind generation curtailment (in some areas up to 60%), due to local over-generation and not enough transmission. The study also counts on substantial transfers to neighboring ISOs, which may not need or want the extra generation due to their own state policies and instantaneous renewable output. So, for cases where wind generation is high, load is insufficient to use it, and neighboring areas cannot take exports from NYS, it would be great to have somewhere for the power to go to create value for NYS residents. Large loads that could be switched on and off when needed, that would benefit the State's GHG goals, would prove to be extremely beneficial. Such loads could be in the form of hydrogen producing plants (electrolysis), or carbon capture facilities (like Carbon Engineering). Smartly sized and strategically located, either at renewable generation locations, or at specific intertie points, dispatchable loads could reduce/eliminate the curtailment of renewable generation. As an example, we could have 500MWs of carbon capture plant capacity that operates nominally at 250MW. The load could be easily ramped up, or down to follow over-generation of renewables resulting from system load, or locational congestion (If you can't dispatch the generation, add dispatchable load). So, technologies for large dispatchable or interruptible loads that improve GHG goals should be identified and developed.

Smart Wires – Maximize the value of the transmission system with active flow control. Smart Wires makes flow controllers for the AC system; Central Hudson has one on the Leeds-Hurley

345kV line. Being able to "dial-in" the loading on a line and direct power flow should allow better use of the existing infrastructure we presently have.

HVDC- there are a few HVDC projects in the NYISO queue, but only one is actually in the current Class Year. The Champlain Hudson Power Express (CHPE) has an application in the NYISO queue for a two-terminal 1250MW line from Quebec, to Astoria in Queens. Its route as planned is to come down the bottom of Lake Champlain to Dresden, then follow Rt 9 and the railway (to within a mile-and-a-half of the Rotterdam Substation and actually through the properties of both New Scotland and Leeds substations), then into the Hudson River for a good stretch, and finally to Astoria. As proposed, it can flow 1250MW from Quebec to NYC, and 250MW the other way. Although this will bring an additional 1250MW of Canadian hydro power to downstate NY, Technology exists for multi-terminal DC lines and they have been built and are operating in other parts of the world. This project, as conceived, is surely a multi-billion dollar project and it makes much more sense to bring on additional partners to make the line more useful to all parties including State residents. I suggest that consideration be given to uprate the line to say 3000MW, and add terminals along the way. Converter station terminal location suggestions include: Plattsburgh – to unbottle a lot of potential wind generation in northern NYS; Sand Bar – to let Vermont in on the action (for a fee) and get some of our northern wind power across the border; Crown Point – to collect the benefit of the proposed 240MW iron mine pumped-hydro energy storage project in Mineville (and add reliability to the radial Ticonderoga circuit); Whitehall – to potentially provide a second major source for places like Global Foundries (and VT); Rotterdam/Princetown – maybe because it's close; New Scotland – important central-east 345kV substation; Leeds – shunt Hudson Valley power directly to NYC. Additionally, having a controllable transmission path with multiple controllable injection points down the eastern side of the Adirondacks could potentially alleviate some of the northern power flow that now all has to traverse west to the Massena/Moses-Utica path only to come back east before it can get downstate. Modelling will be needed to verify the benefit. So, overall, multi-terminal HVDC should be looked at for both upstate applications and collection of offshore wind generation (as we discussed a few weeks ago).

95%+ Efficient Energy Storage – I find it interesting to reflect on REV; I remember Richard Kauffman making the rounds to let everyone know that we have way too much transmission capacity under normal conditions because the system was designed for peak loads. DER and energy storage were the solutions, i.e. generate power close to the load and store a bit if there is too much. Now, it seems, that since renewable generation is being sited everywhere, the NYISO is in the need of much greater transmission capacity to move the remotely generated power to major load centers. Once again the NYISO CARIS study identifies locations of future transmission congestion, even with the (NextEra) Western NY Public Policy Project, (NYPA) Segment A, and (NG) Segment B transmission projects modelled in service. This is because the best locations for renewable generation obviously are nowhere near where the load is, so the power must be shipped a long way. Mega-transmission will be required due to need to oversize renewable generation because of its inherent intermittency and dismal capacity factors. So, as Mr. Kauffman lectured with REV, it's still the peak versus normal line loading issue, only now it is because the renewable generation is likely to be all "on" or "off" at the same time; if it's sunny in far northern NY, all solar will be maxed-out, if it's sunny and windy . . . . well we certainly wouldn't be able to ship all the power out without major line and equipment additions. Once again, some of the transmission construction could be alleviated through the use of energy storage. However, the power would need to be moved at times of low line loading, i.e. at night. But since there is not enough load at night there's really nowhere for it to go unless it could be stored again close to the load. If an energy storage technology existed with high enough efficiencies to allow cascading energy storage in different locations, the need for additional transmission infrastructure might be obviated. Since this scenario would require massive amounts of energy storage both at the source and near the loads, the costs would need to be much less than any of the current battery technologies. New high efficiency energy storage technologies need to be identified and/or developed (they might be some of the new pumped-hydro techniques or ultra-high-pressure hydraulic, etc.).

Run the 765kV Lines at 765kV – There are a bunch of transmission lines in NYS that are designed for 765kV that are operating at 345kV. Considering the cost of new transmission, wouldn't it be smart to run existing infrastructure at its design voltage. One of NYPA's Segment A proposals included operating the Marcy-Knickerbocker (New Scotland) #18 line at 765kV (its design voltage). I still don't know why it wasn't selected as the project. There shouldn't be any true technology barriers for this improvement.

Program / Project Synopsis – ARPAe

ABB

Economical Data-fused Grid Edge Processor (EDGEPRO) for Future Distribution Grid Control Applications

Program: OPEN 2018 Project Term: 02/21/2019 to 02/20/2022 Project Status: ACTIVE

Project State: North Carolina Technical Categories: Grid

ABB Inc. will design a low-cost, secure, and flexible next-generation grid service platform to improve grid efficiency and reliability. This technology will merge advanced edge computing, data fusion and machine learning techniques for virtual metering, and create a central repository for grid applications such as distributed energy resource (DER) control and others on one platform. The united platform will consist of four functional layers: (1) communication including data collection and exchange, (2) data processing and distributed state estimation, (3) data standardization and storage, and (4) hosted grid applications designed to enable large-scale deployment of DERs and more flexible grid control. ABB's approach will integrate and maximize emerging technologies in the transition to a decentralized and distributed electric grid.

Arizona State University (ASU)

Sensor Enabled Modeling of Future Distribution Systems with Distributed Energy Resources

Program: OPEN 2018 Project Term: 08/07/2019 to 08/06/2022 Project Status: ACTIVE

Project State: Arizona Technical Categories: Grid

Arizona State University will develop learning-ready models and control tools to maintain sensor-rich distribution systems in the presence of high levels of DER and storage. This approach will include topology processing algorithms, load and DER models for system planning and operation, distribution system state estimation, optimal DER operational scheduling algorithms, and system-level DER control strategies that leverage inverter controls' flexibility.

The project will alter distribution system operation from today's reactive, load-serving, and outage mitigation-focused approach to an active DER, load, and outage-managed, market-ready approach.

Arizona State University (ASU)

Stochastic Optimal Power Flow

Program: NODES Project Term: 07/11/2016 to 10/10/2020 Project Status: ACTIVE

Project State: Arizona Technical Categories: Grid

Arizona State University (ASU) will develop a stochastic optimal power flow (SOPF) framework, which would integrate uncertainty from renewable resources, load, distributed storage, and demand response technologies into bulk power system management in a holistic manner. The team will develop SOPF algorithms for the security-constrained economic dispatch (SCED) problem used to manage variability in the electric grid. The algorithms will be implemented in a software tool to provide system operators with real-time guidance to help coordinate between bulk generation and large numbers of DERs and demand response. ASU's project features unique data-analytics based short-term forecast for bulk and distributed wind and solar generation utilized by the advisory tool that generates real-time recommendations for market operators based on the SOPF algorithm outputs.

AutoGrid

Integration of Renewables via Demand Management

Program: GENI Project Term: 01/11/2012 to 03/31/2014 Project Status: ALUMNI

Project State: California Technical Categories: Grid

AutoGrid, in conjunction with Lawrence Berkeley National Laboratory and Columbia University, will design and demonstrate automated control software that helps manage real-time demand for energy across the electric grid. Known as the Demand Response Optimization and Management System - Real-Time (DROMS-RT), the software will enable personalized price signals to be sent to millions of customers in extremely short timeframes--incentivizing them to alter their electricity use in response to grid conditions. This will help grid operators better manage unpredictable demand and supply fluctuations in short time-scales--making the power generation process more efficient and cost effective for both suppliers and consumers. DROMS-RT is expected to provide a 90% reduction in the cost of operating demand response and dynamic pricing programs in the U.S.

Bigwood Systems

Global-Optimal Power Flow (G-OPF)

Program: IDEAS Project Term: 03/18/2015 to 06/30/2016 Project Status: ALUMNI

Project State: New York Technical Categories: Grid

Bigwood Systems is developing a comprehensive Optimal Power Flow (OPF) modelling engine that will enhance the energy efficiency, stability, and cost effectiveness of the national electric grid. Like water flowing down a hill, electricity takes the path of least resistance which depends on the grid network topology and on grid controls. However, in a complicated networked environment, this can easily lead to costly congestion or shortages in certain areas of the electric grid. Grid operators use imperfect solutions like approximations, professional judgments, or conservative estimates to try to ensure reliability while minimizing costs. Bigwood Systems' approach will combine four separate analytical technologies to develop an OPF modeling engine that could markedly improve management of the grid. As part of this project, Bigwood Systems will demonstrate the practical applications of this tool in partnership with the California Independent System Operator (CAISO).

Boston University (BU)

Decision-Support Software for Grid Operators

Program: GENI Project Term: 04/19/2013 to 03/31/2016 Project Status: ALUMNI

Project State: Massachusetts Technical Categories: Grid

The Boston University (BU) team is developing control technology to help grid operators more actively manage power flows and integrate renewables by optimally turning entire power lines on and off in coordination with traditional control of generation and load resources. The control technology being developed would provide grid operators with tools to help manage transmission congestion by identifying the facilities whose on/off status must change to lower generation costs, increase utilization of renewable resources and improve system reliability. The technology is based on fast optimization algorithms for the near to real-time change in the on/off status of transmission facilities and their software implementation.

California Institute of Technology (Caltech)

Scalable Distributed Automation System

Program: GENI Project Term: 03/01/2012 to 06/01/2015 Project Status: ALUMNI

Project State: California Technical Categories: Grid

The California Institute of Technology (Caltech) is developing a distributed automation system that allows distributed generators--solar panels, wind farms, thermal co-generation systems--to effectively manage their own power. To date, the main stumbling block for distributed automation systems has been the inability to develop software that can handle more than 100,000 distributed generators and be implemented in real time. Caltech's software could allow millions of generators to self-manage through local sensing, computation, and communication. Taken together, localized algorithms can support certain global objectives, such as maintaining the balance of energy supply and demand, regulating voltage and frequency, and minimizing cost. An automated, grid-wide power control system would ease the integration of renewable energy sources like solar power into the grid by quickly transmitting power when it is created, eliminating the energy loss associated with the lack of renewable energy storage capacity of the grid.

Cornell University

Cloud Computing for the Grid

Program: GENI Project Term: 02/08/2012 to 08/07/2015 Project Status: ALUMNI

Project State: New York Technical Categories: Grid

Cornell University is creating a new software platform for grid operators called GridControl that will utilize cloud computing to more efficiently control the grid. In a cloud computing system, there are minimal hardware and software demands on users. The user can tap into a network of computers that is housed elsewhere (the cloud) and the network runs computer applications for the user. The user only needs interface software to access all of the cloud's data resources, which can be as simple as a web browser. Cloud computing can reduce costs, facilitate innovation through sharing, empower users, and improve the overall reliability of a dispersed system. Cornell's GridControl will focus on 4 elements: delivering the state of the grid to users quickly and reliably; building networked, scalable grid-control software; tailoring services to emerging smart grid uses; and simulating smart grid behavior under various conditions.

Cree

Utility-Scale Silicon Carbide Power Transistors

Program: ADEPT Project Term: 09/01/2010 to 12/31/2014 Project Status: ALUMNI

Project State: North Carolina Technical Categories: Grid

Cree is developing silicon carbide (SiC) power transistors that are 50% more energy efficient than traditional transistors. Transistors act like a switch, controlling the electrical energy that flows through an electrical circuit. Most power transistors today use silicon semiconductors to conduct electricity. However, transistors with SiC semiconductors operate at much higher temperatures, as well as higher voltage and power levels than their silicon counterparts. SiC-based transistors are also smaller and require less cooling than those made with traditional silicon power technology. Cree's SiC transistors will enable electrical circuits to handle higher power levels more efficiently, and they will result in much smaller and lighter electrical devices and power converters. Cree, an established leader in SiC technology, has already released a commercially available SiC transistor that can operate at up to 1,200 volts. The company has also demonstrated a utility-scale SiC transistor that operates at up to 15,000 volts.

Det Norske Veritas (DNV GL)

Internet of Energy for Optimized Distributed Energy Resources

Program: NODES Project Term: 08/15/2016 to 08/14/2019 Project Status: ALUMNI

Project State: Massachusetts Technical Categories: Grid

DNV GL together with its partners, Geli and Group NIRE, will develop an Internet of Energy (IoEn) platform for the automated scheduling, aggregation, dispatch, and performance validation of network optimized DERs and controllable loads. The IoEn platform will simultaneously manage both system-level regulation and distribution-level support functions to facilitate large-scale integration of distributed generation onto the grid. The IoEn will demonstrate a novel and scalable approach for the fast registration and automated dispatch of DERs by combining DNV GL's power system simulation tools and independent third-party validation with Geli's networking, control, and market balancing software. The platform will demonstrate the ability of customer-sited DERs to provide grid frequency regulation and distribution reliability functions with minimal impact to their local behind-the-meter demand management applications. The IoEn will be demonstrated and tested at Group NIRE's utility-connected microgrid test facility in Lubbock, Texas, where it will be integrated with local utility monitoring, control and data acquisition systems. By increasing the number of local devices able to connect and contribute to the IoEn, this project aims to increase renewables penetration above 50% while maintaining required levels of grid performance.

Eaton Corporation

Cloud-Based DER Control

Program: NODES Project Term: 09/01/2016 to 08/31/2020 Project Status: CANCELLED

Project State: Ohio Technical Categories: Grid

Eaton will develop and validate a disruptive cloud-computing-based technology aimed at providing agile and robust synthetic regulating reserve services to the power grid. This approach separates the decision-making of synthetic regulating reserve services into two-levels to significantly reduce the computational complexity, thereby enabling large-scale coordinated control of a vast number of DERs and flexible load. The system-operator level estimates and predicts reserve capacity of the distribution network and decides on the appropriate economic incentives for DERs to participate in future services. At the local level, an energy node comprised of a cluster of DERs and flexible loads will automatically decide its own reserve services strategy that takes into account short-term net load and economic incentives. By splitting these decisions between the two levels, the solution does not require extensive communication or negotiation between the local DERs and the system operators in the cloud.

General Atomics

Low-Insertion HVDC Circuit Breaker

Program: GENI Project Term: 01/09/2012 to 07/31/2013 Project Status: ALUMNI

Project State: California Technical Categories: Grid

General Atomics is developing a direct current (DC) circuit breaker that could protect the grid from faults 100 times faster than its alternating current (AC) counterparts. Circuit breakers are critical elements in any electrical system. At the grid level, their main function is to isolate parts of the grid where a fault has occurred--such as a downed power line or a transformer explosion--from the rest of the system. DC circuit breakers must interrupt the system during a fault much faster than AC circuit breakers to prevent possible damage to cables, converters and other grid-level components. General Atomics' high-voltage DC circuit breaker would react in less than 1/1,000th of a second to interrupt current during a fault, preventing potential hazards to people and equipment.

General Electric (GE) Global Research

Synthetic Reserves from Distributed Flexible Resources

Program: NODES Project Term: 06/10/2016 to 12/09/2019 Project Status: ALUMNI

Project State: Connecticut Technical Categories: Grid

General Electric (GE) Global Research along with its partners will develop a novel distributed flexibility resource (DFR) technology that aggregates responsive flexible loads and DERs to provide synthetic reserve services to the grid while maintaining customer quality-of-service. A key innovation of the project is to develop a forecast tool that will use short-term and real-time weather forecasts along with other data to estimate the reserve potential of aggregate loads and DERs. An optimization framework that will enable aggregation of large numbers of flexible loads and DERs and determine the optimal schedule to bid into the wholesale market will be designed. A scalable control and communication architecture will enable coordination and control of the resources in real-time based on a novel two-tier hierarchical optimal control algorithm.

General Electric (GE) Global Research

High-Power Gas Tube Switches

Program: OPEN 2012 Project Term: 04/30/2013 to 07/31/2017 Project Status: ALUMNI

Project State: Connecticut Technical Categories: Grid

General Electric (GE) Global Research is developing a new gas tube switch that could significantly improve and lower the cost of utility-scale power conversion. A switch breaks an electrical circuit by interrupting the current or diverting it from one conductor to another. To date, solid state semiconductor switches have completely replaced gas tube switches in utility-scale power converters because they have provided lower cost, higher efficiency, and greater reliability. GE is using new materials and innovative designs to develop tubes that not only operate well in high-power conversion, but also perform better and cost less than non-tube electrical switches. A single gas tube switch could replace many semiconductor switches, resulting in more cost effective high power converters.

General Electric (GE) Global Research

Cost-Effective Cable Insulation

Program: GENI Project Term: 02/24/2012 to 05/31/2014 Project Status: ALUMNI

Project State: Connecticut Technical Categories: Grid

General Electric (GE) Global Research is developing new, low-cost insulation for high-voltage direct current (HVDC) electricity transmission cables. The current material used to insulate HVDC transmission cables is very expensive and can account for as much as 1/3 of the total cost of a high-voltage transmission system. GE is embedding nanomaterials into specialty rubber to create its insulation. Not only are these materials less expensive than those used in conventional HVDC insulation, but also they will help suppress excess charge accumulation. The excess charge left behind on a cable poses a major challenge for high-voltage insulation--if it is not kept to a low level, it could ultimately lead the insulation to fail. GE's low-cost insulation is compatible with existing U.S. cable manufacturing processes, further enhancing its cost effectiveness.

GeneSiC Semiconductor

Utility-Scale Silicon Carbide Semiconductor

Program: ADEPT Project Term: 09/01/2010 to 02/28/2013 Project Status: ALUMNI

Project State: Virginia Technical Categories: Grid

GeneSiC Semiconductor is developing an advanced silicon-carbide (SiC)-based semiconductor called an anode-switched thyristor. This low-cost, compact SiC semiconductor conducts higher levels of electrical energy with better precision than traditional silicon semiconductors. This efficiency will enable a dramatic reduction in the size, weight, and volume of the power converters and the electronic devices they are used in. GeneSiC is developing its SiC-based semiconductor for utility-scale power converters. Traditional silicon semiconductors can't process the high voltages that utility-scale power distribution requires, and they must be stacked in complicated circuits that require bulky insulation and cooling hardware. GeneSiC's semiconductors are well suited for high-power applications like large-scale renewable wind and solar energy installations.

Georgia Tech Research Corporation

Autonomous, Decentralized Grid Architecture

Program: GENI Project Term: 01/11/2012 to 02/15/2015 Project Status: ALUMNI

Project State: Georgia Technical Categories: Grid

Georgia Tech Research Corporation is developing a decentralized, autonomous, internet-like control architecture and control software system for the electric power grid. Georgia Tech's new architecture is based on the emerging concept of electricity prosumers--economically motivated actors that can produce, consume, or store electricity. Under Georgia Tech's architecture, all of the actors in an energy system are empowered to offer associated energy services based on their capabilities. The actors achieve their sustainability, efficiency, reliability, and economic objectives, while contributing to system-wide reliability and efficiency goals. This is in marked contrast to the current one-way, centralized control paradigm.

Georgia Tech Research Corporation

Resilient, Cyber Secure Centralized Substation Protection

Program: OPEN 2018 Project Term: 07/12/2019 to 07/11/2022 Project Status:ACTIVE

Project State: Georgia Technical Categories: Grid

The Georgia Tech Research Corporation will design an autonomous, resilient and cyber-secure protection and control system for each power plant and substation on its grid. This will eliminate complex coordinated protection settings and transform the protection practice into a simpler, intelligent, automated and transparent process. The technology will integrate protective relays into an intelligent protection scheme that relies on existing high data redundancy in substations to (a) validate data; (b) detect hidden failures and in this case self-heal the protection and control system; (c) detect cyber-attacks (focus on false data and/or malicious control injection) and identify the source for attribution; and (d) provide the full state of the system with minimal delay for optimal full state feedback control.

Georgia Tech Research Corporation

Utility-Scale Power Router

Program: ADEPT Project Term: 09/01/2010 to 01/31/2013 Project Status: ALUMNI

Project State: Georgia Technical Categories: Grid

Georgia Tech Research Corporation is developing a cost-effective, utility-scale power router that uses an enhanced transformer to more efficiently direct power on the grid. Existing power routing technologies are too expensive for widespread use, but the ability to route grid power to match real-time demand and power outages would significantly reduce energy costs for utilities, municipalities, and consumers. Georgia Tech is adding a power converter to an existing grid transformer to better control power flows at about 1/10th the cost of existing power routing solutions. Transformers convert the high-voltage electricity that is transmitted through the grid into the low-voltage electricity that is used by homes and businesses. The added converter uses fewer steps to convert some types of power and eliminates unnecessary power storage, among other improvements. The enhanced transformer is more efficient, and it would still work even if the converter fails, ensuring grid reliability.

Georgia Tech Research Corporation

Modular Solid State Transformers

Program: CIRCUITS Project Term: 02/12/2018 to 02/11/2020 Project Status: ACTIVE

Project State: Georgia Technical Categories: Grid

Georgia Tech Research Corporation and its project team will develop a solid-state transformer for medium-voltage grid applications using silicon carbide with a focus on compact size and high-performance. Traditional grid connected transformers have been used for over 100 years to 'step down' higher voltage to lower voltage. Higher voltages allows for delivery of power over longer distances and lower voltages keeps consumers safe. But traditional distribution transformers lack integrated sensing, communications, and controls. They also lack the ability to control the voltage, current, frequency, power factor or anything else to improve local or global performance. Solid-state transformers can provide improvements and Georgia Tech's design seeks to address major roadblocks to their implementation, namely insulation, cooling, voltage change, and magnetic field issues, as well as downstream protection against abnormal current faults. If successful, the team will greatly increase transformer functionality while reducing its size over current technologies, affecting application areas like grid energy storage, solar photovoltaics and electric vehicle fast chargers, while also enabling better grid monitoring and easy retrofits.

GridBright

Secure Grid Data Exchange Using Cryptography, Peer-to-Peer Networks, and Blockchain Ledgers

Program: OPEN 2018 Project Term: 02/15/2019 to 02/14/2022 Project Status: ACTIVE

Project State: California Technical Categories: Grid

GridBright will develop a simple and secure solution for sharing grid-related data to improve grid efficiency, reliability, and resiliency in a manner that preserves security and integrity. GridBright will use the Agile development model to construct several proof-of-concept software pipelines, performing penetration and compromise testing and a quantitative evaluation of each against existing requirements. The solution will create a simpler secure grid data exchange process for the electric grid and utility industries.

GridBright

Power Systems Model Repository

Program: GRID DATA Project Term: 05/25/2016 to 05/24/2019 Project Status: ALUMNI

Project State: California Technical Categories: Grid

GridBright and Utility Integration Solutions (UISOL, a GE Company) will develop a power systems model repository based on state-of-the-art open-source software. The models in this repository will be used to facilitate testing and adoption of new grid optimization and control algorithms. The repository will use field-proven open-source software and will be made publicly available in the first year of the project. Key features of the repository include an advanced search capability to support search and extraction of models based on key research characteristics, faster model upload and download times, and the ability to support thousands of users. The team will establish a long-term strategy for managing the repository that will allow its operation to continue after its project term with ARPA-E ends.

Harvard University

Transistor-less Power Supply Technology

Program: IDEAS Project Term: 06/01/2017 to 11/30/2018 Project Status: ALUMNI

Project State: Massachusetts Technical Categories: Grid

Harvard University in partnership with Sandia National Laboratories will develop a transistor-less 16kW DC to DC converter boosting a 0.5kV DC input to 8kV that is scalable to 100kW. If successful, the transistor-less DC to DC converter could improve the performance of power electronics for electric vehicles, commercial power supplies, renewable energy systems, grid operations, and other applications. Converting DC to DC is a two-step process that traditionally uses fast-switching transistors to convert a DC input to an AC signal before the signal is rectified to a DC output. The Harvard and Sandia team will improve the process by replacing the active, fast-switching transistors with a slow switch followed by a passive, nonlinear transmission line (NLTL). The NLTL is a ladder network of passive components (inductors and diodes) that provide a nonlinear output with voltage. The combination of the nonlinear behavior with dispersion converts a quasi-DC input into a series of sharper and taller (amplified) voltage pulses called solitons, thus executing the DC to AC conversion without the use of active, fast-switching transistors. The NLTL will be followed by a high breakdown voltage silicon carbide and/or gallium nitride diode-based accumulator that converts the series of solitons to a DC output. Replacing the fast-switching transistors with a slow switch and a NLTL addresses the cost, size, efficiency, and reliability issues associated with fast switching based converters. Diodes also cost less and last longer because they are simpler structures than transistors and use no dielectrics. Efficiency, cost, and reliability improvements provided by a NLTL-based power converter will drastically benefit commercial power supplies, industrial motors, electric vehicles, data centers, the electric grid, and renewable electric power generation such as solar and wind.

HexaTech

Semiconductors that Improve Electricity Flow

Program: OPEN 2012 Project Term: 02/05/2013 to 05/31/2016 Project Status: ALUMNI

Project State: North Carolina Technical Categories: Grid

HexaTech is developing new semiconductors for electrical switches that will more efficiently control the flow of electricity across high-voltage electrical lines. A switch helps control electricity: switching it on and off, converting it from one voltage to another, and converting it from an Alternating Current (A/C) to a Direct Current (D/C) and back. Most switches today use silicon or silicon-based semiconductors, which are not able to handle high voltages, fast switching speeds, or high operating temperatures. HexaTech has developed highest quality, single crystalline Aluminum Nitride (AlN) semiconductor wafers. HexaTech AlN wafers are the enabling platform for power converters which can handle 50 times more voltage than silicon, as well as higher switching speeds and operating temperatures.

Illinois Institute of Technology (IIT)

Solid State Circuit Breakers for Microgrids

Program: CIRCUITS Project Term: 12/18/2017 to 12/17/2020 Project Status: ACTIVE

Project State: Illinois Technical Categories: Grid

Illinois Institute of Technology (IIT) will develop autonomously operated, programmable, and intelligent bidirectional solid-state circuit breakers (SSCB) using transistors based on gallium nitride (GaN). Renewable power sources and other distributed energy resources feed electricity to the utility grid through interfacing power electronic converters, but the power converters cannot withstand a fault condition (abnormal electric current) for more than a few microseconds. Circuit faults cause either catastrophic destruction or protective shutdown of the converters, resulting in loss of power reliability. Traditional mechanical circuit breakers are too slow to address this challenge. The team's proposed SSCB technology offers a programmable response time to as short as one microsecond, well within the overload-withstanding capability of power converters, and enables a distribution system-level ability to isolate a fault from the rest of the power system before renewable power generation is interrupted. Their design produces a 1000x decrease in response time and 5x reduction in cost in comparison to commercial mechanical circuit breakers. If successful, such devices could be used to help protect microgrids and enable higher penetration of renewable energy sources.

Michigan State University (MSU)

Power Flow Controller for Renewables

Program: GENI Project Term: 02/08/2012 to 11/15/2015 Project Status: ALUMNI

Project State: Michigan Technical Categories: Grid

Michigan State University (MSU) is developing a power flow controller to improve the routing of electricity from renewable sources through existing power lines. The fast, innovative, and lightweight circuitry that MSU is incorporating into its controller will eliminate the need for a separate heavy and expensive transformer, as well as the construction of new transmission lines. MSU's controller is better suited to control power flows from distributed and intermittent wind and solar power systems than traditional transformer-based controllers are, so it will help to integrate more renewable energy into the grid. MSU's power flow controller can be installed anywhere in the existing grid to optimize energy transmission and help reduce transmission congestion.

National Renewable Energy Laboratory (NREL)

SMARTDATA Grid Models

Program: GRID DATA Project Term: 08/24/2016 to 11/30/2020 Project Status: ACTIVE

Project State: Colorado Technical Categories: Grid

The National Renewable Energy Laboratory (NREL), with partner MIT-Comillas-IIT, will develop combined distribution-transmission power grid models. The team will create distribution models using a version of Comillas' Reference Network Model (RNM) that will be adapted to U.S. utilities and based on real data from a broad range of utility partners. The models will be complemented by the development of customizable scenarios that can be used for accurate algorithm comparisons. These scenarios will take into account unknown factors that affect the grid, such as future power generation technologies, increasing distributed energy resources, varying electrical load, disruptions due to weather events, and repeatable contingency sequences. These enhanced datasets and associated data building tools are intended to provide large-scale test cases that realistically describe potential future grid systems and enable the nation's research community to more accurately test advanced algorithms and control architectures. MIT-Comillas-IIT will assist NREL with the distribution model creation. Alstom Grid will assist in validating the distribution models.

National Renewable Energy Laboratory (NREL)

Real-time Distributed Energy Resource Optimization

Program: NODES Project Term: 07/19/2016 to 01/18/2020 Project Status: ALUMNI

Project State: Colorado Technical Categories: Grid

The National Renewable Energy Laboratory (NREL) lead team will develop a comprehensive distribution network management framework that unifies real-time voltage and frequency control at the home/DER controllers' level with network-wide energy management at the utility/aggregator level. The distributed control architecture will continuously steer operating points of DERs toward optimal solutions of pertinent optimization problems, while dynamically procuring and dispatching synthetic reserves based on current system state and forecasts of ambient and load conditions. The control algorithms invoke simple mathematical operations that can be embedded on low-cost microcontrollers, and enable distributed decision making on time scales that match the dynamics of distribution systems with high renewable integration.

National Rural Electric Cooperative Association (NRECA)

Autonomous Load Control

Program: NODES Project Term: 08/15/2016 to 08/14/2019 Project Status: ALUMNI

Project State: Virginia Technical Categories: Grid

The National Rural Electric Cooperative Association (NRECA) will develop GridBallast, a low-cost demand-side management technology, to address resiliency and stability concerns accompanying the exponential growth in DERs deployment in the U.S. electric grid. Specifically, devices based on GridBallast technology will monitor grid voltage and frequency and control the target load in order to address excursions from grid operating targets. The devices will operate autonomously to provide rapid local response, removing the need for costly infrastructure to communicate with a central controller. If the devices are installed with an optional radio, they will be able to support traditional demand response through peer-to-peer collaborative operation from a central operator. The team includes experts from Carnegie Mellon University, Eaton Corporation, and SparkMeter, and will focus development on two specific devices: a water heater controller, and a smart circuit controller. The GridBallast project aims to improve resiliency and reduce the cost of demand side management for voltage and frequency control by at least 50% using a streamlined design and removing the need for extensive communications infrastructure.

New York University (NYU)

Grid Dynamics from City Light

Program: IDEAS Project Term: 01/01/2018 to 05/31/2019 Project Status: ALUMNI

Project State: New York Technical Categories: Grid

New York University (NYU) will develop an observational platform to remotely reveal energy usage patterns of New York City using synoptic imaging of the urban skyline. The electrical grid of the future will be a complex collection of traditional centralized power generation, distributed energy resources, and emerging renewable energy technologies. Advanced energy consumption data is required to design and optimize our future grid. At present, the costly and time-consuming installation of smart meters is the only way to obtain this level of building energy information. NYU will harness astronomical lessons from the study of light emitted by stars to propose a method to understand city-level energy consumption using a single platform. This platform will develop proxy measures of energy consumption, monitor the health of the electric grid, and characterize end use. The project will use three different imaging methodologies to measure interior lights at night: persistent broadband visible, hypertemporal, and hyperspectral. Broadband visible imaging of an urban skyline will measure changes in the city lightscape. This variability serves as a proxy for occupancy and behavior patterns that, when combined with "ground truth" meter data, will be used to train models to quantify energy use. Hypertemporal visible imaging can detect and classify tiny changes over time in the oscillations of electrical lights. For urban lightscapes, phase changes in individual units can signal changes in load (e.g. appliances turning on/off), while neighborhood-level changes can indicate the health of distribution transformers. The information from these methods can serve as a low-cost supplement (and potential alternative) to smart meters. Hyperspectral observations, including bands of infrared light not visible by the human eye, allow the team to distinguish lighting technologies at night. By combining this data with their broadband visible observations, the team can uniquely quantify energy use phenomena such as technology penetration and "rebound," where the energy benefits of energy efficient lighting are partially offset by greater use. With these results, utility companies can design targeted outreach efforts to incentivize energy conservation at the consumer level. Utility providers can use these insights to improve grid resilience, preemptively detect outages, and more effectively manage assets in real time. If successful, the system is well suited to deployment in developing countries where the use of modern energy-monitoring technologies is prohibitively expensive.

Newton Energy Group

Gas-Electric Co-Optimization

Program: OPEN 2015 Project Term: 04/11/2016 to 07/19/2019 Project Status: ALUMNI

Project State: Massachusetts Technical Categories: Grid

The team led by Newton Energy Group will lead the Gas-Electric Co-Optimization (GECO) project to improve coordination of wholesale natural gas and power operators both at the physical and market levels. The team's approach uses mathematical methods and computational techniques that have revolutionized the field of optimal control. These methods will be applied to natural gas pipeline networks, and the final deliverable will consist of three major components. First, they will model and optimize intra-day pipeline operations represented by realistic models of gas network flow. Next, the team will develop economic theory and computation algorithms for the pricing of natural gas delivered to end users, in particular to gas-fired power plants. Finally, they will combine these two analytical components to design practical market mechanisms for efficient coordination of gas and electric systems. The goal of efficient market design is to develop a mechanism under which access to pipeline capacity will be provided on the basis of its economic value as determined by gas buyers and sellers, and not on the current allocation of physical capacity rights. The tool guarantees natural gas will be available when power plants need it, and that the power produced can be sold to consumers at a price sufficient to cover the cost of the natural gas.

Northwestern University

Frequency-Based Load Control Architecture

Program: NODES Project Term: 06/15/2016 to 12/14/2019 Project Status: ALUMNI

Project State: Illinois Technical Categories: Grid

Northwestern University and its partners will develop a frequency-based load control architecture to provide additional frequency response capability and allow increased renewable generation on the grid. The work will focus on developing and demonstrating algorithms that adapt to rapid changes of loads, generation, and system configuration while taking into account various constraints arising from the transmission and distribution networks. The multi-layer control architecture makes it possible to simultaneously ensure system stability at the transmission network level, control frequency at the local distribution network level, and maintain the quality-of-service for individual customers at the building level, all under a single framework. At the transmission level, coordination among different areas will be achieved through a centralized scheme to ensure stable frequency synchronization, while the control decisions within a single area will be made based on local information. The efficiency of the centralized scheme will be ensured by decomposing the network into smaller components on which the control problem is solved individually. At the local distribution network level, the control scheme will be decentralized, in which control decisions are made based on the state of the neighboring nodes. At the building level, dynamic models for flexible appliances and DERs will be developed and used to design algorithms to optimally follow a given aggregated load profile.

Oak Ridge National Laboratory (ORNL)

Magnetic Amplifier for Power Flow Control

Program: GENI Project Term: 02/24/2012 to 06/30/2017 Project Status: ALUMNI

Project State: Tennessee Technical Categories: Grid

Oak Ridge National Laboratory (ORNL) is developing an electromagnet-based, amplifier-like device that will allow for complete control over the flow of power within the electric grid. To date, complete control of power flow within the grid has been prohibitively expensive. ORNL's controller could provide a reliable, cost-effective solution to this problem. The team is combining two types of pre-existing technologies to assist in flow control, culminating in a prototype iron-based magnetic amplifier. Ordinarily, such a device would require expensive superconductive wire, but the magnetic iron core of ORNL's device could serve as a low-cost alternative that is equally adept at regulating power flow.

Opcondys

Transformerless Converter Topology

Program: CIRCUITS Project Term: 01/17/2018 to 01/16/2021 Project Status: ACTIVE

Project State: California Technical Categories: Grid

Opcondys will develop a high-voltage power converter design for energy storage systems connected directly to the power grid. Opcondys' converter design will use a modified switched multiplier topology that will allow connection to utility transmission lines without intervening step-up transformers. It uses a photonic, wide bandgap power switching device called the Optical Transconductance Varistor. This is a fast, high-voltage, bidirectional device which reduces the number of circuit elements required for charging and discharging the storage element. By operating at 100 kHz it is possible to increase efficiency to 99% compared to 95-98% efficiency of traditional converters. The system also reduces the size of the passive elements by 50% and, because of the optical control, mitigates electromagnetic interference issues. The elimination of step-up transformers further reduces system size, and can enable a lower cost than existing systems. If successful, project developments could open the door to increased integration of grid-level energy storage.

Pacific Northwest National Laboratory (PNNL)

Power-Grid Optimization

Program: OPEN 2015 Project Term: 07/19/2016 to 04/18/2020 Project Status: ACTIVE

Project State: Washington Technical Categories: Grid

The team led by Pacific Northwest National Laboratory (PNNL) will develop a High-Performance Power-Grid Optimization (HIPPO) technology to reduce grid resource scheduling times to within a fraction of current speeds, which can lead to more flexible and reliable real-time operation. The team will leverage advances in optimization algorithms and deploy high-performance computing technologies to significantly improve the performance of grid scheduling. HIPPO will provide inter-algorithm parallelization and allow algorithms to share information during their solution process, with the objective of reducing computing time by efficiently using computational power. New algorithms will leverage knowledge of the underlying system, operational experience, and past solutions to improve performance and avoid previously encountered mistakes.

Pacific Northwest National Laboratory (PNNL)

Sustainable Data Evolution Technology

Program: GRID DATA Project Term: 09/07/2016 to 01/18/2019 Project Status: ALUMNI

Project State: Washington Technical Categories: Grid

The Pacific Northwest National Laboratory (PNNL), along with the National Rural Electric Cooperative Association, PJM, Avista, and CAISO, will develop a sustainable data evolution technology (SDET) to create open-access transmission and distribution power grid datasets as well as data creation tools that the grid community can use to create new datasets based on user requirements and changing grid complexity. The SDET approach will derive features and metrics from many private datasets provided by PNNL's industry partners. For transmission systems, PNNL will develop advanced, graph-theory based techniques and statistical approaches to reproduce the derived features and metrics in synthetic power systems models. For distribution systems, the team will use anonymization and obfuscation techniques and apply them to datasets **from utility partners.**

Pacific Northwest National Laboratory (PNNL)

Data Repository for Power System Models

Program: GRID DATA Project Term: 07/01/2016 to 06/30/2020 Project Status: ACTIVE

Project State: Washington Technical Categories: Grid

The Pacific Northwest National Laboratory (PNNL) has partnered with the National Rural Electric Cooperative Association (NRECA) to build a power system model repository, which will maintain and develop open-access power grid models and data sets. The DR POWER approach will review, annotate, and verify submitted datasets while establishing a repository and a web portal to distribute open-access models and scenarios. Through the portal, users can explore the curated data, create suitable datasets (which may include time variation), review and critique models, and download datasets in a specified format. Key features include the ability to collaboratively build, refine, and review a range of large-scale realistic power system models. For researchers, this represents a significant improvement over the current open availability of only small-scale, static models that do not properly represent the challenging environments encountered by present and future power grids. The repository and the web portal will be hosted in PNNL's Electricity Infrastructure Operations Center with access to petabytes of computing storage and load-balancing across multiple computing resources.

Pacific Northwest National Laboratory (PNNL)

Incentive-Based Control of Distributed Assets

Program: NODES Project Term: 09/06/2016 to 09/05/2019 Project Status: ALUMNI

Project State: Washington Technical Categories: Grid

Pacific Northwest National Laboratory (PNNL) will develop and test a hierarchical control framework for coordinating the flexibility of a full range of DERs, including flexible building loads, to supply reserves to the electric power grid. The hierarchical control framework consists of incentive-based control strategies across multiple time-scales. The system will use a slower incentive-based approach to acquire flexible assets that provide services, combined with faster device-level controls that use minimal communication to provide desired responses to the grid. Each DER that chooses to participate will communicate its ability to provide flexibility and the time scale over which it can provide the service. A distribution reliability coordinator will act as an interface between the DERs and the bulk system, coordinating the resources in an economic and reliable manner. The team will characterize various DER types to quantify the maximum flexibility that can be extracted from a collection of DERs in aggregate in order to provide service-level guarantees to the bulk energy market operator. The performance of the resulting hierarchical control system will be tested at scale in a co-simulation environment spanning transmission, distribution, ancillary markets, and communication systems.

Pacific Northwest National Laboratory (PNNL)

Real-Time Transmission Optimization

Program: OPEN 2012 Project Term: 04/12/2013 to 07/17/2016 Project Status: ALUMNI

Project State: Washington Technical Categories: Grid

Pacific Northwest National Laboratory (PNNL) is developing innovative high-performance-computing techniques that can assess unused power transmission capacity in real-time in order to better manage congestion in the power grid. This type of assessment is traditionally performed off-line every season or every year using only conservative, worst-case scenarios. Finding computing techniques that rate transmission capacity in real-time could improve the utilization of the existing transmission infrastructure by up to 30% and facilitate increased integration of renewable generation into the grid--all without having to build costly new transmission lines.

Pacific Northwest National Laboratory (PNNL)

High Performance Adaptive Deep-Reinforcement-Learning-based Real-time Emergency Control (HADREC) to Enhance Power Grid Resilience in Stochastic Environment

Program: OPEN 2018 Project Term: 08/16/2019 to 08/18/2022 Project Status: ACTIVE

Project State: Washington Technical Categories: Grid

Pacific Northwest National Laboratory (PNNL) will construct an intelligent, real-time emergency control system to help safeguard the U.S. electric grid by providing effective and fast control actions to system operators in response to large contingencies or extreme events. PNNL's scalable platform will utilize advanced machine learning techniques (deep-meta-reinforcement learning) as well as high-performance computing to automatically provide effective emergency control strategies seconds after disturbances or attacks. Platform development will focus on the determination, timing, coordination, and automation of control actions, including adaptation under uncertainty. The technology will diminish the need for costly preventive security measures as well as reduce action time sixtyfold and system recovery time by at least 10%, enabling more efficient and resilient grid operation.

PingThings

A National Infrastructure for Artificial Intelligence on the Grid

Program: OPEN 2018 Project Term: 08/12/2019 to 08/11/2022 Project Status: ACTIVE

Project State: California Technical Categories: Grid

PingThings will develop a national infrastructure for analytics and artificial intelligence (AI) on the power grid using a three-pronged approach. First, a scalable, cloud-based platform will store, process, analyze, and visualize grid sensor data. Second, massive open and accessible datasets will be created through (a) deploying grid sensors to capture wide-scale and localized grid behavior, (b) simulating and executing grid models to generate virtual sensor data, and (c) establishing a secure data exchange mechanism. Third, a diverse research community will be developed through focused educational content, online code sharing, and data and AI competitions. The project's goal is to accelerate the development of data-driven use cases to improve grid operation and analysis.

ProsumerGrid

Distribution Operator Simulation Studio

Program: OPEN 2015 Project Term: 06/01/2016 to 08/30/2019 Project Status: ALUMNI

Project State: Georgia Technical Categories: Grid

ProsumerGrid, with its partners, will develop a highly specialized and interactive software tool capable of simulating the operation of emerging DSOs at the physical, information, and market levels while capturing the interactions among the various market participants. The software will offer electricity industry analysts, engineers, economists, and policy makers a "design studio environment" in which various propositions of participant roles, market rules, business processes, and services exchange can be studied to achieve a robust DSO design. The software will utilize a powerful decentralized decision-making algorithm, and extend state-of-the-art grid solvers with the ability to develop DER scheduling, DSO market rules, and energy service transactions. The tool could ensure correctness and reduce risk in upcoming regulatory decisions as various states move towards the formation of DSOs.

RamGoss

High-Performance Transistors

Program: OPEN 2012 Project Term: 02/11/2013 to 08/10/2014 Project Status: ALUMNI

Project State: Massachusetts Technical Categories: Grid

RamGoss is using innovative device designs and high-performance materials to develop utility-scale electronic switches that would significantly outperform today's state-of-the-art devices. Switches are the fundamental building blocks of electronic devices, controlling the electrical energy that flows around an electrical circuit. Today's best electronic switches for large power applications are bulky and inefficient, which leads to higher cost and wasted power. RamGoss is optimizing new, low-cost materials and developing a new, completely different switch designs. Combined, these innovations would increase the efficiency and reduce the overall size and cost of power converters for a variety of electronic devices and grid-scale applications, including electric vehicle (EV) chargers, large-scale wind plants, and solar power arrays.

Rensselaer Polytechnic Institute (RPI)

High-Power Transistor Switch

Program: OPEN 2012 Project Term: 03/07/2013 to 03/06/2016 Project Status: ALUMNI

Project State: New York Technical Categories: Grid

Rensselaer Polytechnic Institute (RPI) is working to develop and demonstrate a new bi-directional transistor switch that would significantly simplify the power conversion process for high-voltage, high-power electronics systems. A transistor switch helps control electricity, converting it from one voltage to another or from an Alternating Current (A/C) to a Direct Current (D/C). High-power systems, including solar and wind plants, usually require multiple switches to convert energy into electricity that can be transmitted through the grid. These multi-level switch configurations are costly and complex, which drives down their overall efficiency and reliability. RPI's new switch would require fewer components than conventional high-power switches. This simple design would in turn simplify the overall power conversion process and enable renewable energy sources to more easily connect to the grid.

Sandia National Laboratories

Probability-Based Software for Grid Optimization

Program: GENI Project Term: 04/01/2012 to 01/16/2015 Project Status: ALUMNI

Project State: New Mexico Technical Categories: Grid

Sandia National Laboratories is working with several commercial and university partners to develop software for market management systems (MMSs) that enable greater use of renewable energy sources throughout the grid. MMSs are used to securely and optimally determine which energy resources should be used to service energy demand across the country. Contributions of electricity to the grid from renewable energy sources such as wind and solar are intermittent, introducing complications for MMSs, which have trouble accommodating the multiple sources of price and supply uncertainties associated with bringing these new types of energy into the grid. Sandia's software will bring a new, probability-based formulation to account for these uncertainties. By factoring in various probability scenarios for electricity production from renewable energy sources in real time, Sandia's formula can reduce the risk of inefficient electricity transmission, save ratepayers money, conserve power, and support the future use of renewable energy.

Sandia National Laboratories

TRANSFORMERS FOR A MODERNIZED GRID

Program: OPEN 2018 Project Term: 05/06/2019 to 05/06/2022 Project Status: ACTIVE

Project State: New Mexico Technical Categories: Grid

Sandia National Laboratories will develop advanced core materials for grid-level electrical transformers, improving their efficiency and resiliency. Current transformers feature copper windings surrounding a magnetic core. The project team's new core material seeks to increase electrical efficiency by at least 10% while enabling a 50% reduction in transformer size. The core will be robust, withstanding EMPs and GMDs that threaten today's grid. Sandia will also develop additives that can be added to the oil in existing transformers as a retrofit as well as included in new transformers. One additive will dramatically increase the heat conduction away from the transformer windings during high-current events by transitioning to a heat-conducting solid at high temperature. Another additive will react with the existing dielectric Kraft paper, cross-linking reactive groups on the paper and restoring the integrity of the insulation. These additives will increase the resiliency and robustness of existing and new transformers to EMP and GMD events.

Sandia National Laboratories

[Power Conversion with Photoconductive Switches]

Program: IDEAS Project Term: 05/01/2017 to 10/31/2018 Project Status: ALUMNI

Project State: New Mexico Technical Categories: Grid

Sandia National Laboratories will develop a new type of switch, a 100kV optically controlled switch (often called photoconductive semiconductor switch or PCSS), based on the WBG semiconductors GaN and AlGaN. The capabilities of the PCSS will be demonstrated in high-voltage circuits for medium and high voltage direct current (MVDC/HVDC) power conversion for grid applications. Photoconductivity is the measure of a material's response to the energy inherent in light radiation. The electrical conductivity of a photoconductive material increases when it absorbs light. The team will first measure the photoconductive properties of GaN and AlGaN in order to assess if they operate similarly to gallium arsenide, a conventional semiconductor material used for PCSS, demonstrating sub-bandgap optical triggering and low-field, high-gain avalanche providing many times as many carriers by the electric field as created by the optical trigger. These two effects provide a tremendous reduction in the optical trigger energy required to activate the switch. The team will then design and fabricate GaN and AlGaN-based photoconductive semiconductor switches. The team predicts that WBG PCSS will outperform their predecessors with higher switch efficiency, the ability to switch at higher voltages, and will turn-off and recover faster, allowing for a higher frequency of switching. Ultimately, this will enable high-voltage switch assemblies (50-500kV) that can be triggered from a single, small driver (e.g. semiconductor laser). These modules will be substantially smaller (~10x) and simpler than existing modules used in grid-connected power electronics, allowing the realization of inexpensive and efficient switch modules that can be used in DC to AC power conversion systems on the grid at distribution and transmission scales.

Siemens

ReNew100 - Reliable Power System Operation with 100% Renewable Generation

Program: OPEN 2018 Project Term: 04/05/2019 to 04/04/2022 Project Status: ACTIVE

Project State: New Jersey Technical Categories: Grid

Siemens will develop an operator support system and grid planning functionality that enable a power system to operate with 100% inverter-based renewable generation from wind and solar. ReNew100 features automatic Controller Parameter Optimization and model calibration technologies that help ensure power system reliability as the generation mix changes. Successful test results will be a milestone toward the goal of a stable and reliable power system obtaining a majority of total electrical energy sourced from variable wind and solar.

Silicon Power

[Optical Switches for High-Power Systems]

Program: OPEN 2012 Project Term: 05/15/2013 to 08/10/2015 Project Status: CANCELLED

Project State: Pennsylvania Technical Categories: Grid

Silicon Power is developing a semiconducting device that switches high-power and high-voltage electricity using optical signals as triggers for the switches, instead of conventional signals carried through wires. A switch helps control electricity, converting it from one voltage or current to another. High-power systems generally require multiple switches to convert energy into electricity that can be transmitted through the grid. These multi-level switch configurations use many switches which may be costly and inefficient. Additionally, most switching mechanisms use silicon, which cannot handle the high switching frequencies or voltages that high-power systems demand. Silicon Power is using light to trigger its switching mechanisms, which could greatly simplify the overall power conversion process. Additionally, Silicon Power's switching device is made of silicon carbide instead of straight silicon, which is more efficient and allows it to handle higher frequencies and voltages.

Smart Wire Grid

Distributed Power Flow Control

Program: GENI Project Term: 04/23/2012 to 09/30/2014 Project Status: ALUMNI

Project State: California Technical Categories: Grid

Smart Wire Grid is developing a solution for controlling power flow within the electric grid to better manage unused and overall transmission capacity. The 300,000 miles of high-voltage transmission line in the U.S. today are congested and inefficient, with only around 50% of all transmission capacity utilized at any given time. Increased consumer demand should be met in part with a more efficient and economical power flow. Smart Wire Grid's devices clamp onto existing transmission lines and control the flow of power within--much like how internet routers help allocate bandwidth throughout the web. Smart wires could support greater use of renewable energy by providing more consistent control over how that energy is routed within the grid on a real-time basis. This would lessen the concerns surrounding the grid's inability to effectively store intermittent energy from renewables for later use.

Stanford University

Distributed Energy Resource Networks

Program: NODES Project Term: 07/27/2016 to 03/25/2020 Project Status: ACTIVE

Project State: California Technical Categories:Grid

Stanford University will develop Powernet, an open-source and open architecture platform for scalable and secure coordination of consumer flexible load and DERs. Powernet will be based on the principle of connecting information networks to the power network (connecting bits and watts). It uses a layered architecture that enables real-time coordination of centralized resources with millions of DERs by integrating embedded sensing and computing, power electronics, and networking with cloud computing. The team will develop a Home Hub system capable of networking with existing inverters and appliances in a home and controlling power via smart switches that replace traditional fuses. The Home Hub will also use algorithms for aggregating local customer resources to meet local constraints and global coordination objectives. A cloud-based cloud coordinator platform will be developed that executes optimization and monitoring functions to coordinate Home Hubs by minimizing costs while increasing aggregate consumer quality-of-service.

Switched Source

Unified Power Flow Controller

Program: CIRCUITS Project Term: 09/29/2017 to 03/28/2020 Project Status: ACTIVE

Project State: Illinois Technical Categories: Grid

Switched Source will develop a power-electronics based hardware solution to fortify electric distribution systems, with the goal of delivering cost-effective infrastructure retrofits to match rapid advancements in energy generation and consumption. The company's power flow controller will improve capabilities for routing electricity between neighboring distribution circuit feeders, so that grid operators can utilize the system as a more secure, reliable, and efficient networked platform. The topology the team is incorporating into its controller will eliminate the need for separate heavy and expensive transformers, as well as the costly construction of new distribution lines and substations in many cases. The power flow controller's low weight and small size means that it can be installed anywhere in the existing grid to optimize energy distribution and help reduce congestion. If successful, implementation of Switched Source's power flow controller will also significantly increase hosting capacity and connectivity for distributed renewable generation. During a prior ARPA-E GENI award, this team developed this platform technology. Now, as an addition to the ARPA-E CIRCUITS program, the team will further its research.

Texas Engineering Experiment Station (TEES)

Automated Grid Disruption Response System

Program: GENI Project Term: 03/01/2012 to 06/30/2015 Project Status: ALUMNI

Project State: Texas Technical Categories: Grid

Texas Engineering Experiment Station (TEES) is using topology control as a mechanism to improve system operations and manage disruptions within the electric grid. The grid is subject to interruption from cascading faults caused by extreme operating conditions, malicious external attacks, and intermittent electricity generation from renewable energy sources. The Robust Adaptive Topology Control (RATC) system is capable of detecting, classifying, and responding to grid disturbances by reconfiguring the grid in order to maintain economically efficient operations while guaranteeing reliability. The RATC system would help prevent future power outages, which account for roughly $80 billion in losses for businesses and consumers each year.

Minimizing the time it takes for the grid to respond to expensive interruptions will also make it easier to integrate intermittent renewable energy sources into the grid.

University of California, Berkeley (UC Berkeley)

Measuring Phase Angle Change in Power Lines

Program: OPEN 2012 Project Term: 03/01/2013 to 06/30/2018 Project Status: ALUMNI

Project State: California Technical Categories: Grid

The University of California, Berkeley (UC Berkeley) is developing a device to monitor and measure electric power data from the grid's distribution system. The new instrument--known as a micro-phasor measurement unit (µPMU)--is designed to measure critical parameters such as voltage and phase angle at different locations, and correlate them in time via extremely precise GPS clocks. The amount of phase angle difference provides information about the stability and direction of power flow. Data collected from a network of these µPMUs would facilitate better monitoring and control of grid power flow--a critical element for integrating intermittent and renewable resources, such as rooftop solar and wind energy, and other technologies such as electric vehicles and distributed storage.

University of California, San Diego (UC San Diego)

Distributed Grid Control of Flexible Loads

Program: NODES Project Term: 06/13/2016 to 12/12/2019 Project Status: ALUMNI

Project State: California Technical Categories: Grid

The University of California, San Diego (UC San Diego) will develop coordination algorithms and software using intelligent control and optimization for flexible load and DERs to provide reliable frequency regulation services for the bulk power grid. The project will develop a multi-layer framework for larger-scale energy aggregators to act on behalf of their smaller-sized customers to help respond to incoming requests from regional transmission operators. The team will develop approaches that aggregators can use to quantify reserves, system objectives and constraints, customer usage patterns, and generation forecasts. Aggregators will use distributed coordination algorithms to rapidly respond to operators while considering network constraints and quality of services for customers. The UC San Diego technology to manage flexible loads and DERs offers economic and operational advantages for utilities, operators and customers.

University of Illinois, Urbana-Champaign (UIUC)

Synthetic Data for Power Grid R&D

Program: GRID DATA Project Term: 06/20/2016 to 12/31/2018 Project Status: ALUMNI

Project State: Illinois Technical Categories: Grid

The University of Illinois, Urbana-Champaign (UIUC), with partners from Cornell University, Virginia Commonwealth University, and Arizona State University will develop a set of entirely synthetic electric transmission system models. Their 10 open-source system models and associated scenarios will match the complexity of the actual power grid. By utilizing statistics derived from real data, the team's models will have coordinates based on North American geography with network structure, characteristics, and consumer demand that mimics real grid profiles. Smaller models will be based on smaller areas, such as part of a U.S. state, while the large models will cover much of the continent. All models and their scenarios will be validated using security-constrained optimal power flows, with parameters tuned to emulate the statistical characteristics of actual transmission system models.

University of Illinois, Urbana-Champaign (UIUC)

Power Grid Security

Program: OPEN 2012 Project Term: 04/05/2013 to 08/31/2016 Project Status: ALUMNI

Project State: Illinois Technical Categories: Grid

The University of Illinois, Urbana-Champaign (UIUC) is developing scalable grid modeling, monitoring, and analysis tools that would improve its resiliency to system failures as well as cyber attacks, which can significantly improve the reliability of grid operations. Power system operators today lack the ability to assess the grid's reliability with respect to potential cyber failures and attacks. UIUC is using theoretical and practical techniques from both the cyber security and power engineering domains to develop new algorithms and software tools capable of analyzing real-world threats against power grid critical infrastructures including cyber components (e.g. communication networks), physical components (e.g. power lines), and interdependencies between the two in its models and simulations. Continuing the project work started by UIUC, Avista Utilities is now developing technology to automatically extract and map electrical switch information to generate cyber-physical models. These cyber-physical models can be used to identify network vulnerabilities as well as identify and prioritize critical assets which will allow utilities and others to conduct simulations, perform analysis, and fortify networks against cyber-attacks.

University of Michigan

OVERCOMING THE TECHNICAL CHALLENGES OF COORDINATING DISTRIBUTED LOAD RESOURCES AT SCALE

Program: OPEN 2018 Project Term: 06/12/2019 to 06/11/2022 Project Status: ACTIVE

Project State: Michigan Technical Categories: Grid

The University of Michigan will develop load-control strategies to improve grid reliability in the face of increased penetration of DERs and low-cost renewable generation. As the electricity generation mix changes to include more renewables and DERs, load shifting is essential. Today, there are few load-shifting strategies in use at grid scale that are capable of balancing current levels of intermittent energy production. The team will develop three testing environments to identify issues the grid faces with increased levels of energy from distributed and renewable generation. Their method could improve credibility for load-control mechanisms at scale and lower costs to power providers and consumers alike.

University of Michigan

Transmission System Data Set

Program: GRID DATA Project Term: 05/27/2016 to 11/26/2018 Project Status: ALUMNI

Project State: Michigan Technical Categories: Grid

The University of Michigan, with partners from Los Alamos National Laboratory, the California Institute of Technology, and Columbia University, will develop a transmission system data set with greater reliability, size, and scope compared to current models. The project combines existing power systems data with advanced obfuscation techniques to anonymize the data while still creating realistic models. In addition, the project delivers year-long test cases that capture grid network behavior over time, enabling the analysis of optimization algorithms over different time scales. These realistic datasets will be used to develop synthetic test cases to examine the scalability and robustness of optimization algorithms. The team is also developing a new format for capturing power system model data using JavaScript Object Notation and will provide open-source tools for data quality control and validation, format translation, synthetic test case generation, and obfuscation. Finally, the project aims at developing an infrastructure for ensuring replicable research and easing experimentation, using the concept of virtual machines to enable comparison of algorithms as hardware and software evolve over time.

University of Minnesota (UMN)

Rapidly Viable and Sustained Grid

Program: OPEN 2018 Project Term: 07/01/2019 to 06/30/2022 Project Status: ACTIVE

Project State: Minnesota Technical Categories: Grid

The University of Minnesota (UMN) will develop a net-load management framework that rapidly identifies neighborhood-units to support grid infrastructure and enable ultrafast coordinated management. UMN's project will rethink power recovery from near blackout conditions with a focus on rapid energization and maximizing power duration. This project's approach could fundamentally change the way large contingencies are managed. It would transition power systems and critical infrastructure from fragile to robust using intelligent, self-organizing control for coordinating resources, enhancing resiliency and increasing the use of renewable energy sources. The communication and control layer coupled with rapid decision-making methods for managing local sources and loads will coordinate power resources and leverage renewable energy. This framework will support the grid in contingencies such as failure of aging infrastructure or catastrophic weather events.

University of Minnesota (UMN)

Enabling the Grid of the Future

Program: NODES Project Term: 07/15/2016 to 09/30/2019 Project Status: ALUMNI

Project State: Minnesota Technical Categories: Grid

The University of Minnesota (UMN) will develop a comprehensive approach that addresses the challenges to system reliability and power quality presented by widespread renewable power generation. By developing techniques for both centralized cloud-based and distributed peer-to-peer networks, the proposed system will enable coordinated response of many local units to adjust consumption and generation of energy, satisfy physical constraints, and provide ancillary services requested by a grid operator. The project will apply concepts from nonlinear and robust control theory to design self-organizing power systems that effectively respond to the grid events and variability. A key feature enabled by the proposed methodology is a flexible plug-and-play architecture wherein devices and small power networks can easily engage or disengage from other power networks or the grid. The project's design approach will be tested across many different scenarios while using more than 100 actual physical devices such as photovoltaics, battery storage inverters, and home appliances.

University of Tennessee (UT)

Smart and Flexible Microgrid

Program: OPEN 2015 Project Term: 06/24/2016 to 12/23/2020 Project Status: ACTIVE

Project State: Tennessee Technical Categories: Grid

University of Tennessee (UT), along with their partners, will develop a new type of microgrid design, along with its corresponding controller. Like most other microgrids, it will have solar PV-based distributed generation and be capable of grid-connected or disconnected (islanded) operations. Unlike other microgrids, this design will incorporate smart grid capabilities including intelligent switches and high-speed communication links. The included controller will accommodate and utilize these smart grid features for enhanced performance and reduced costs. The microgrid controller will be open source, offering a flexible and robust development and implementation environment. The microgrid and controller design will also be scalable for different geographic areas, load sizes, distributed generation source number and types, and even multiple microgrids within an area.

University of Vermont (UVM)

Packetized Energy Management

Program: NODES Project Term: 05/25/2016 to 05/24/2021 Project Status: ACTIVE

Project State: Vermont Technical Categories: Grid

The University of Vermont (UVM) will develop and test a new approach for demand-side management called packetized energy management (PEM) that builds on approaches used to manage data packets in communication networks without centralized control and with a high level of privacy. The PEM system will allow millions of small end-use devices to cooperatively balance energy supply and demand in real time without jeopardizing the reliability of the grid or the quality of service to consumers. The project will develop the PEM method to optimally manage the rapid fluctuations that come with large amounts of renewable power generation, while simultaneously managing reliability constraints in the bulk transmission and local distribution infrastructure. To ensure UVM's PEM methods are effective, the integrated system will undergo extensive simulation testing with large-scale hardware implementation for the bulk **power grid and an industry-scale micro-grid environments.**

University of Washington (UW)

Renewable Energy Positioning System

Program: GENI Project Term: 03/01/2012 to 10/14/2015 Project Status: ALUMNI

Project State: Washington Technical Categories: Grid

The University of Washington (UW) and the University of Michigan are developing an integrated system to match well-positioned energy storage facilities with precise control technologies so the electric grid can more easily include energy from renewable power sources like wind and solar. Because renewable energy sources provide intermittent power, it is difficult for the grid to efficiently allocate those resources without developing solutions to store their energy for later use. The two universities are working with utilities, regulators, and the private sector to position renewable energy storage facilities in locations that optimize their ability to provide and transmit electricity where and when it is needed most. Expanding the network of transmission lines is prohibitively expensive, so combining well-placed storage facilities with robust control systems to efficiently route their power will save consumers money and enable the widespread use of safe, renewable sources of power.

University of Wisconsin-Madison (UW-Madison)

EPIGRIDS Transmission System Models

Program: GRID DATA Project Term: 08/11/2016 to 02/29/2020 Project Status: ACTIVE

Project State: Wisconsin Technical Categories: Grid

The University of Wisconsin-Madison (UW-Madison) and its partners will develop realistic transmission system models and scenarios that will serve as test cases to reduce barriers to the development and adoption of new technologies in grid optimization and control. The EPIGRIDS project aims to construct realistic grid models by using software to emulate the transmission and generation expansion decision processes used by utility planners. This synthetic model development will utilize Geographic Information Systems (GIS) data on population density, industrial and commercial energy consumption patterns, and land use, over sizes ranging from the city-level to continental-scale. In order to test the robustness of the system's solutions, it will allow users to tailor specific data sets and scenarios to challenge particular aspects of optimization and control algorithm development. Flexible methodologies for data set construction and connecting features of these data sets to geographically described energy use and land use constraints will enable collaborative development of new models, far beyond those directly delivered by this project.

Vanderbilt University

Software for Smarter Grids

Program: OPEN 2015 Project Term: 04/04/2016 to 03/03/2020 Project Status: ACTIVE

Project State: Tennessee Technical Categories: Grid

Vanderbilt University will develop a foundation platform for developing and deploying robust, reliable, effective and secure software applications for the Smart Grid. The Resilient Information Architecture Platform for the Smart Grid (RIAPS) provides core services for building effective and powerful smart grid applications. It offers unique services for real-time data dissemination, fault tolerance, and coordination across apps distributed over the network. The platform will allow plug-and-play architecture by providing a software layer that isolates the hardware details making software applications portable across multiple devices and enabling interoperability among heterogeneous devices and applications. Additionally, the RIAPS will be supported by a model-driven development toolchain to reduce development costs. The platform will allow apps to be upgraded and dynamically reconfigured in the field and will enable a marketplace of hardware device vendors, app developers, and end users to sell and buy products and services that will interoperate. Vanderbilt's team will develop and prototype the platform using an open source code base. The team will also construct representative open source energy management software apps that will demonstrate the effectiveness and dependability of the system, while offering a starting point for commercial implementations. The team expects the platform to become an industry standard on which Smart Grid applications can reliably run, much in the same way Android and iOS have become industry standard platforms for smartphones.

Varentec

Dynamic Power Flow Controller

Program: GENI Project Term: 01/03/2012 to 05/31/2016 Project Status:ALUMNI

Project State: California Technical Categories: Grid

Varentec is developing compact, low-cost transmission power controllers with fractional power rating for controlling power flow on transmission networks. The technology will enhance grid operations through improved use of current assets and by dramatically reducing the number of transmission lines that have to be built to meet increasing contributions of renewable energy sources like wind and solar. The proposed transmission controllers would allow for the dynamic control of voltage and power flow, improving the grid's ability to dispatch power in real time to the places where it is most needed. The controllers would work as fail-safe devices whereby the grid would be restored to its present operating state in the event of a controller malfunction instead of failing outright. The ability to affordably and dynamically control power flow with adequate fail-safe switchgear could open up new competitive energy markets which are not possible under the current regulatory structure and technology base.

Program: PERFORM—Performance-based Energy Resource Feedback, Optimization, and Risk Management

National Renewable Energy Laboratory – Golden, CO

An Integrated Paradigm for the Management of Delivery Risk in Electricity Markets: From Batteries to Insurance and Beyond - $3,408,526

The National Renewable Energy Laboratory (NREL)-led project team will develop an operating paradigm that leverages flexibility from distributed and bulk resources to cost-effectively manage delivery risk of intermittent resources, like solar and wind. Today, flexibility from a limited number of Distributed Energy Resources (DERs) is offered in wholesale energy markets, and the value of flexibility is not yet recognized for economic hedging of delivery risk. The project team will develop transparent and verifiable risk scores for DERs that combine insights from advanced artificial intelligence methods and domain expertise. The team's risk scores will quantify asset delivery risk and inform bidding strategies of aggregators and utilities. To acknowledge the value of flexibility for economic hedging, the project team will investigate how the economic efficiency of power system operations could change when a flexibility auction is added to energy markets and novel insurance products are offered.

Energy and Environmental Economics, Inc. – San Francisco, CA

Deploying E3's RESERVE Tool to Enable Advanced Operation of Clean Grids - $595,000

E3 will partner with the California Independent System Operator (CAISO), the operator of California's electricity grid, to develop the existing E3 RESERVE modeling tool into a publicly available tool that can help enable more efficient grid operations to reduce costs and improve the utilization of large-scale renewable electricity resources, distributed energy resources, and conventional power generation technologies. RESERVE is designed to enable dynamic determination of essential grid services under high levels of variable renewable electricity production. RESERVE will use machine learning to continuously improve forecasts of system reserve needs to maintain the real-time balance of supply and demand on the electric grid. The team will create a database of historical forecast errors and other data as well as a model of CAISO's grid to evaluate how RESERVE performs compared with CAISO's existing models. If successful, the RESERVE tool will be customizable for other grid operators.

Rensselaer Polytechnic Institute – Troy, NY

Risk Segmentation and Portfolio Analysis for Pareto Dominance in High Renewable Penetration and Storage Reserves - $2,664,000

Rensselaer Polytechnic Institute will develop market mechanism and risk assessment techniques to support cost-effective and risk-informed integration of renewable energy resources into the grid. The team will holistically apply risk segmentation, adaptive credit scoring, and network-based portfolio analysis techniques from financial engineering and risk management for risk analytics of power systems in an approach that integrates asset and system levels. The team will introduce risk segmentation of an asset's throughput by applying tranching similar to collateralized debt obligations, and will analyze the system-wide risk in meeting an increasingly stochastic demand with supply at different time scales using network-based portfolio analysis techniques. Adaptive risk scores will help to determine the type of services for which generation and/or storage assets' service tranches are most suitable.

Lehigh University – Bethlehem, PA

Application of Banking Scoring and Rating for Coherent Risk Measures in Electricity Systems - $2,500,623

Lehigh University will develop a framework for asset and system risk management that can be incorporated into current electricity system operations to improve economic efficiency through the establishment of an electric assets risk bureau. Currently, discrepancies exist between the power scheduled by a system operator and actual power generated and/or consumed. To address this issue, Lehigh will use scoring and rating concepts from banking and financial institutions as well as optimization methods in dispatching power systems to help system operators and electricity markets schedule resources. Lehigh's research will counteract two failures in electricity system operations—imperfect information and missing markets for risk management products—by developing risk scores at the asset level with the collected historical data and incorporating scoring into decision making at the system level.

Castalune, LLC – Boston, MA

Predicting Events to Enable Robust Renewable Grids - $1,770,760

Castalune will develop a software system that identifies and monitors complex leading indicators of key grid events associated with individual assets and regional grids, such as price volatility events, curtailment, and reliability failure. The team will produce new risk metrics and evaluation methodologies that inform generator dispatch within electric grids subject to increasingly dynamic underlying drivers of demand (e.g., electric vehicles, on-site generation, or storage) and supply (e.g., weather-driven renewable generation, storage). The project will garner early-stage engagement from industry leaders, including utilities and renewable energy operators, facing similar challenges in managing highly dynamic grids, with the intent of helping them transition from conventional generation sources toward renewable energy and storage sources while maintaining grid reliability.

Tabors Caramanis Rudkevich, Inc. – Newton, MA

Stochastic Nodal Adequacy Platform (SNAP) - $2,000,000

Tabors Caramanis Rudkevich's (TCR) Stochastic Nodal Adequacy Platforms (SNAP) will determine the value of resource adequacy for the electric power industry given significant penetration of intermittent and distributed generation. SNAP is based on the premise that uncertainty in resource availability characterizes real-time utility operations. As such, SNAP will probabilistically measure operational uncertainty and economic risk for system operators and asset owners to calculate individual contributions to system adequacy and produce a nodal adequacy pricing structure for consumers. SNAP's added economic efficiency will reduce fossil fuel use and risk to large-scale integration of intermittent technologies.

Georgia Institute of Technology – Atlanta, GA

Risk-Aware Market Clearing for Power Systems (RAMC) - $3,250,000

The increasing role of renewable energy sources is challenging grid operations, which have traditionally relied on highly predictable load and generation. Future grid operations must balance generation costs and system-level risk, shifting from deterministic to stochastic optimization and risk management. The Risk-Aware Market Clearing (RAMC) project will provide a blueprint for an end-to-end, data-driven approach where risk is explicitly modeled, quantified, and optimized, striking a tradeoff between cost and system-level risk minimization. The RAMC project focuses on challenges arising from increased stochasticity in generation, load, flow interchanges with adjacent markets, and extreme weather. RAMC addresses these challenges through innovations in machine learning, sampling, and optimization. Starting with the risk quantification of each individual asset obtained from historical data, RAMC learns the correlations between the performance and risk of individual assets, optimizes the selection of asset bundles, and quantifies the system-level risk.

Energy Trading Analytics, LLC – Phoenixville, PA

Stochastic Market Auction Redesigned Trading System (SMARTS) - $3,360,000

The proposed effort is to develop a novel, state-of-the-art stochastic redesign for wholesale real-time energy and reserve markets coupled with intelligent energy-portfolio risk management tools that enable consumers to prioritize their flexible demand assets (such as air conditioners, water heaters, energy storage) to offer their flexibility into markets as demand reserves. This project will evaluate the risk and performance of the proposed market trading system and conduct simulation and pre-pilot tests to demonstrate the approach in the world's largest wholesale electricity market, PJM Interconnection. The redesigned market trading system will advance price-responsive risk management, foster robust decentralized decision making for real-time operations and operational planning under uncertainty, and attract innovation and investment opportunities.

Boston University – Boston, MA

A New Risk Assessment and Management Paradigm (NewRAMP) in Electricity Markets - $3,000,000

The proposed work offers a New Risk Assessment and Management Paradigm (NewRAMP) in the evolving electric power sector, which comprises cascaded/decreasing look-ahead timeframe markets that co-optimize energy and reserves provided/demanded by assets with stochastic and correlated capacities. NewRAMP develops innovative approaches for quantifying the risk of individual assets based on their performance and ability to deliver on their assumed obligations. NewRAMP effectively translates this risk to the system level to increase the efficiency of power system operation and planning in the presence of extensive market participation by "risky" assets. NewRAMP synthesizes ideas and theories from finance and insurance, operations research, power system engineering, and electricity market design into methodologies constituting a risk-driven paradigm to achieve higher adoption of stochastic resources and more efficient and reliable system operation.

Duke University – Durham, NC

A Grid that's Risk-Aware for Clean Electricity – GRACE - $2,437,443

A Grid that's Risk-Aware for Clean Electricity (GRACE) is an energy management system (EMS) framework for characterizing the uncertainty of electric power system assets to optimize their performance. The proposed EMS determines the scheduling, dispatch, and compensation of different resources in organized wholesale electricity markets and vertically integrated utilities by building upon industry-implemented market structure and algorithms to incorporate risk considerations. The team will characterize uncertainty of grid asset performance, determine risk-aware reserve targets and asset commitment and dispatch, and translate performance uncertainty into risk scores and associated compensation for energy and reserves. GRACE will be ready for seamless near-term integration into industry practice and reduce system-wide costs and emissions.

B
COST BENEFIT ANALYSIS BACKGROUND

Guide for Conducting Benefit-Cost Evaluation of Realized Impacts of Public R&D Programs

Guide for Conducting Benefit-Cost Evaluation of Realized Impacts of Public R&D Programs

Revised working draft, August 2011

Prepared by:
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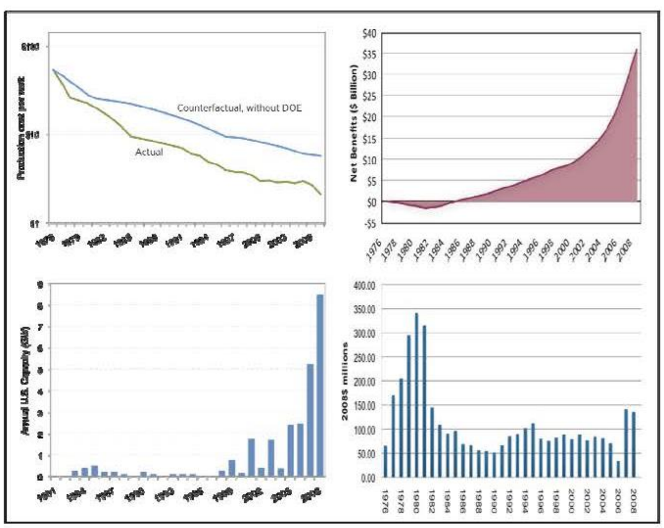
Prepared for:
U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy



Guide for Conducting Benefit-Cost Evaluation of Realized Impacts of Public R&D Programs

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Table of Contents

Guide for Conducting Benefit-Cost Evaluation of Realized Impacts of Public R&D Programs

Part I. Background, Benefit-Cost Overview and Special Features

I.1 Background

This document provides guidance for evaluators who conduct impact assessments to determine the "realized" economic benefits and costs, energy, environmental benefits, and other impacts of the Office of Energy Efficiency and Renewable Energy's (EERE) R&D programs. The focus of this Guide is on realized outcomes or impacts of R&D programs actually experienced by American citizens, industry, and others. Retrospective evaluations may be contrasted to prospective evaluations that reflect expected or potential outcomes only if assumptions hold.

The retrospective approach described in this Guide is based on realized results only and the extent they can be attributed to the efforts of an R&D program. While it has been prepared specifically to guide retrospective benefit-cost analysis of EERE R&D Programs, this report may be used for similar analysis of other public R&D organizations.

Directives and guidance from the executive and legislative branches set impact evaluation expectations for EERE and other Federal programs. These are listed in Attachment 1.

EERE retrospective benefit-cost evaluations must be performed by independent professional evaluators guided by the procedures outlined in this peer-reviewed Guide.[1] Evaluators are also expected to be guided by the *Guiding Principles for Evaluators* provided by the American Evaluation Association and listed in Attachment 2. Although a degree of customization will be necessary based on the selected technologies under examination and the available data, the goal is to ensure that a basic consistency in method, approach, and convention is applied and maintained across such studies.[2]

[1] An earlier draft of this Guide was peer reviewed by external experts in November 2009. See Acknowledgements for list of members of expert panel who reviewed the earlier version of this Guide.

[2] Commissioned evaluators are expected to follow the Guide in performing EERE retrospective benefit-cost studies unless specifically exempted from its coverage. They are encouraged to read the Guide at the outset of proposing or planning an R&D impact evaluation study.

The impacts assessments covered in this Guide are intended to address the following questions of interest to managers of the Department of Energy (DOE), Congress, the general public, and other stakeholders:

1. To what extent has EERE produced energy and economic benefits relative to the next best alternative?
2. To what extent has EERE achieved environmental benefits, and enhanced energy security?
3. To what extent has EERE cultivated a knowledge-base in the research community that has impacted innovations in today's markets?
4. Would today's commercialized technologies likely have happened at the same time, and with the same scope and scale, without EERE's efforts?
5. To what extent do benefits attributable to EERE involvement exceed EERE expenditures? Was the public investment worth it?

The assessment approach outlined in this Guide produces impact results findings for the metrics defined in Table I-1. In addition to energy and economic impacts, the approach quantifies air emissions reduction, environmental health benefits (e.g., averted mortality and morbidity and other health effects, and dollars of health cost avoidance), certain energy security benefits, and knowledge creation and diffusion as reflected by patents and publications. It addresses attribution of benefits through the use of a counterfactual model which seeks to compare outcomes with what would likely have happened in the absence of the R&D program.

Directives for Evaluation of Federal Programs

Impact evaluation questions for R&D programs are motivated by the desire of program managers to efficiently and effectively manage their R&D portfolios to make the best use of public investments provided by the American people. Consistent with this aim are a host of past and recent Government directives for impact evaluation of Federal Programs. Over the past several years there have been multiple directives from the executive and legislative branches that set program evaluation expectations for federal programs, as listed in Attachment 1.

A federal energy R&D program that has determined, through systematic retrospective evaluation, its net benefits is better positioned to communicate its value to its agency leadership, Congress, stakeholders, and the public than one who lacks documented evidence. Systematic retrospective evaluation also informs program managers about possible ways to improve their programs and to position them for the future by revealing strengths and weaknesses in past performance.

The impact results quantified from the analysis provide a conservative estimate for three reasons:

1) The approach strives to be fully retrospective in its coverage and thereby avoids reliance on forecasted data having a higher degree of uncertainty; nevertheless, benefits in most cases are expected to continue past the cut-off year of the analysis.
2) The approach takes into account a portfolio rather than a single project; however, it includes the benefits of only a few technologies developed by a program or

subprogram while taking into account total program costs to be weighed against the partial benefits.

3) Not all benefits assessed are valued in monetary terms (e.g., the effects of Greenhouse Gases and energy security are expressed in tons of CO2 and equivalent barrels of imported oil avoided, respectively.[3])

Thus, the approach is empirical-based, and the results are more conservative than studies that (a) include forecasted effects, (b) take a project-approach rather than a portfolio-approach, (c) consider only project costs, and (d) use non-verified approaches to benefits estimation.

As such, the results determined from the analysis described in this Guide provide a **first order, lower bound estimate** of the energy, economic, environmental, security, and knowledge benefits a program has contributed to the nation. This determination of conservative impact results is to be fully described and documented in all final study reports.

The economic benefit-cost method used in evaluation studies supported by this Guide is designed to be applied to a portfolio (or cluster) of technologies, such as an entire program or subprogram. It should be noted, however, that in some cases the individual technologies selected within a cluster study may be appropriately treated as a group (e.g., a group of closely related infrastructure technologies), and in other cases each selected technology within a cluster will be more appropriately treated as an individual case study. This means that there will be some differences in the details of analyses across studies, as each study seeks to provide the most credible analysis possible for the types of technologies evaluated and the data available. This makes it possible for each individual study to stand on its own in terms of the validity of its analysis, and is to be preferred over applying an overly simplified, crude rule-of-thumb, one-size-fits-all (and less accurate) approach to benefit-cost studies.

The method presented in this Guide builds on the R&D impact assessment approach used by the National Institute of Standards and Technology (NIST),[4] and improves on the approach employed by the National Research Council (NRC) in their 2001 study *"Energy Research at DOE: Was It worth It?"* An overview of how the approach offered in this Guide makes changes to the earlier NRC approach, as well as a more detailed comparison of the two, is provided in Attachment 3.

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[3] The review panel did not think that the existing approaches to valuation of these environmental and security effects had sufficient levels of confidence for inclusion without unduly increasing the level of uncertainty in overall results. Analysis of these effects in dollar terms could be performed as a separate analysis and reported as supplemental results.

[4] NIST, through its former Advanced Technology Program (ATP), pioneered in cluster benefit-cost studies to assess portfolios of projects rather than single projects. See, for example, Thomas Pelsoci (2005, 2007), and O'Connor, Rowe, Gallaher, et al. (2007). These ATP cluster studies, however, unlike the current EERE approach, considered only economic benefits and not the other categories of benefits included in the EERE benefit-cost cluster approach.

Table I-1. Impact evaluation metrics covered in this Guide

Outcomes	Units
Economic Performance Metrics	
• Gross economic benefits	Millions or billions of dollars
• Net economic benefits (NB) (undiscounted) [1]	Millions or billions of dollars
• Net present value (NPV)[2] at 3% and 7% discount rates	Millions or billions of dollars
• Internal rate of return (IRR) on public investment [4]	Percent
• Benefit-to-cost ratio (BCR) at 3% and 7% 5	Ratio
Energy Benefits	
• Energy saved	Trillion Btu
• Renewable capacity	Mega watts (MW)
Environmental Benefits	
Air Emissions Reduction	
• Avoided carbon dioxide emissions (CO_2)	Million metric tons of CO_2 (MMTC)
• Avoided sulfur dioxide emissions (SO_2)	Tons
• Avoided nitrogen oxide (NOx)	Tons
• Avoided particulate matter emissions (PM)	Tons
Health Cost Avoidance	Tons
• Reduced morbidity (e.g., avoided respiratory symptoms, chronic bronchitis, nonfatal heart attacks) and mortality	Mortality & morbidity rates
• Health costs avoided due to reduced air emissions	Millions or billions of dollars
Energy Security Benefits	
• Displaced petroleum consumption • Natural gas displacement • Effect on energy infrastructure	Billions of gallons of gasoline equivalent (GGE); millions of cubic feet of natural gas;; barrels of imported oil equivalent (BOE) Description
Knowledge Benefits	
• Patents, publications, and other knowledge outputs and outcomes	Types and numbers of outputs, citation rates, linkages to EERE-sponsored R&D, Citation Index values, identification of notable patents, knowledge spillovers shown by linkages to other technologies and industries
Acceleration Effect (as appropriate)	Years the research achievement has advanced due to EERE R&D efforts

Notes:

[1] Net Benefits equal benefits minus costs, with no discounting applied to the cash flow.

[2] Net present value (NPV) equals the present value of the investment's net positive cash flow, minus the present value of the initial investment. A positive NPV means that benefits exceed cost by more than enough to cover all costs including the required rate of return expressed by inclusion of the discount rate in the calculations.

[3] OMB issued Circular A94 (1992) and Circular A-4 (2003) that provide directives on discount rates for federal benefit-cost analysis.

[4] Internal rate of return (IRR) is a percentage yield on an investment, found as the solution value interest rate that equates benefits and costs, resulting in a Net Present Value (NPV) of zero. The IRR is compared against the investor's minimum acceptable rate of return (also known as the hurdle rate) to ascertain the economic attractiveness of the investment. If the IRR equals or exceeds the hurdle rate, the investment is economic; if it is less than the hurdle rate, it is uneconomic.

[5] Equals the present value benefits divided by present value investment costs. A ratio greater than one means that benefits exceed costs.

As of the end of 2010, the initial draft of this Guide had been used successfully in the conduct of four EERE benefit-cost cluster studies begun in 2009, and published in 2010 and 2011. Feedback and "lessons learned" compiled from the first four benefit-cost cluster studies have been used to produce this edition of the Guide.

It is expected that, as methodological advances emerge, including those resulting from the experiences of evaluators engaged in other DOE-commissioned evaluation studies, the Guide will be updated to reflect the state-of-the-art in the conduct of impact evaluations for R&D programs. In addition to fostering best practices in impact evaluation, another objective of the Guide is to ensure that basic consistency in approach across studies is maintained.

Part I, Sections 2 and 3 of this Guide provide background on the benefit-cost method and highlight special features of this extended cluster approach. Then, in Part II, Sections 1 through 8, the Guide provides detailed step-by-step instructions to independent evaluators who are contracted to perform retrospective benefit-cost cluster studies using this methodology. Examples from the four completed studies illustrate the approach.

I.2 Overview of Traditional Economic Benefit-Cost Analysis

This section provides a general description of traditional benefit-cost method, as used to estimate the economic performance metrics in Table I-1. It is provided both to show how economic benefits and related performance metrics are derived, and to provide a point of departure for adding to the traditional benefit-cost approach the expanded features described in section I.3 of this Guide.

Dollar Benefits versus Dollar Costs

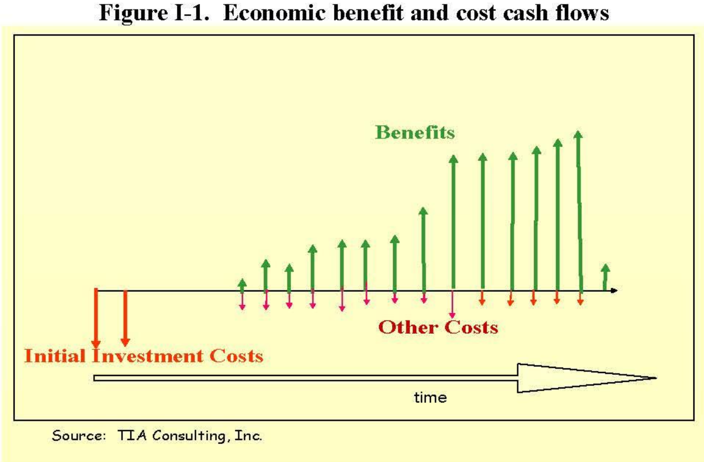
Traditional benefit-cost analysis weighs the monetary value of economic benefits of an investment against its costs to determine if it was (or, in the case of prospective analysis, is expected to be) economically worthwhile. The dollar amounts are tracked as cash flows over time in order to adjust them for the time value of money—both for changes in the purchasing power of the dollar (due to inflation or deflation) and for the real opportunity cost of capital.

The cash-flow model of Figure I-1 illustrates economic benefit and cost cash flows over time. The down-pointing arrows depict costs. The upward-pointing arrows depict benefits, which would include energy savings in the analysis of energy efficiency and renewable energy programs. Investment costs (i.e., program cluster costs) are identified as such; operating, maintenance, and repair costs in each year are typically netted out against that year's benefits.

Cash-Flow Time Adjustments

As noted above, cash flows occurring at different times must be adjusted both for changes in the purchasing power of the dollar and for the real opportunity of capital. It is possible to make the adjustments for timing differences in cash flows in **either** of the following two ways: (1) First a price deflator index can be applied to the "current" (actual) dollar amounts occurring at different times to adjust them to "constant dollars" whereby each dollar has equivalent purchasing power as of a stated base year, and then an appropriate discount formula (or derived discount factors) can be applied to the constant dollar amounts, based on an interest rate, or "discount rate," that reflects the "real" return to capital apart from changes in dollar purchasing power. (2) Both timing adjustments can be done at once by applying to the "current (actual) dollar" cash flows (without first adjusting them to constant dollars) an appropriate discount formula (or derived discount factors) based on a discount rate that reflects the "nominal" (market) return to capital.

Figure I-1. Economic benefit and cost cash flows



The result of applying either of these procedures is to express the whole of a stream of cash flows over time as either a lump-sum equivalent amount at a stated point in time, or as an equivalent uniform annual (or monthly) amount, depending on the discount formulas used. The procedure of converting a stream of cash flows over time to a time-equivalent amount at another time is often called "discounting cash flows" and the interest rate used in the discounting calculations is called the "discount rate."[5]

[5] This referenced use of "discounting" and "discount rate" is specifically within the context of capital investment analysis, as distinct from use of similar terms with different meanings in other contexts.

OMB Directives on Discounting and Discount rates

The approach for Federal benefit-cost analysis is subject to White House Office of Management and Budget (OMB) directives.[6] OMB Circular A-94, issued in 1992, directs the use of a 7% real discount rate for Federal benefit-cost analysis.[7] A more recent guidance is provided by OMB Circular A-4, issued in 2003, which pertains to benefit-cost analysis used as a tool for regulatory analysis. As Circular A-4 notes, Circular A-94 states that a real discount rate of 7% should be used in benefit-cost analysis—as an estimate of the average before-tax rate of return to private capital in the U.S. economy. This rate is an approximation of the opportunity cost of capital. Circular A-4 further notes that OMB found in a subsequent analysis that the average rate of return to capital remained near 7%. It also points out that Circular A-94 recommends using other discount rates to show the sensitivity of the estimates to the discount rate assumption, and notes that the average real rate of return on long-term government debt has averaged about 3%. It directs the use of both a 3% and a 7% real discount rate for a benefit-cost analysis conducted for regulatory purposes.

Economic Performance Measures

Use of multiple economic performance measures best meets the preferences of different audiences and help to broaden communication. There are multiple, closely related measures that are widely used to express the economic performance of an evaluated investment. Figure I-2 below summarizes three economic performance measures widely used in benefit-cost studies. These three measures are used to assess if, and to what extent, benefits attributed to a designated project, program, sub-program, or other portfolio exceeded the public investment.

(1) Net Present Value Benefits (NPV): Total present value benefits minus total present value costs.

A positive NPV means that benefits exceed cost by more than enough to cover all costs including the required rate of return expressed by inclusion of the discount rate in the calculations. The larger the NPV, the greater the extent that benefits exceed costs, and the more worthwhile is a project, other things being equal.

(Net Benefits (NB) may be shown as undiscounted (i.e., assuming a 0% required rate of return or 0% discount rate), emphasizing the effect of discounting using positive rates.) The undiscounted results is designated NB in Table I-1.

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[6] OMB Circulars are available at www.whitehouse.gov/omb/circulars.

[7] OMB Circular No. A-94, Oct. 29, 1992. "Guidelines and Discount Rates for Benefit-Cost Analysis of Federal Programs." The 1992 issue of Circular No. A-94 states that a 7% real discount rate should be used for benefit-cost analysis. In December 2008, an updated release of OMB Circular No. A-94 provided Appendix C that provided revised discount rates for Cost-Effectiveness, Lease Purchase, and Related Analyses. However, Appendix C and the cover letter accompanying the release stated that the circular applies to cost-effectiveness and lease-buy decisions, rather than benefit-cost studies. Thus, Appendix C to OMB Circular No. A-94 is not considered applicable to the benefit-cost approach given in this Guide.

(2) Benefit-to-Cost Ratio (B/C or BCR): Present value benefits (less non-investment costs[8]) divided by present value investment costs.

A ratio greater than one means that benefits exceed costs. A ratio of 10, for example, means that 10 dollars are generated in benefits on average for every one dollar of costs incurred and taking into account the required rate of return expressed by inclusion of the discount rate in the calculations.

(3) Internal rate of return (IRR): The IRR is a percentage yield found as the solution value interest rate that, when used in the appropriate discounting formulas, will equate benefits and costs, resulting in an NPV of zero. The yield is useful for comparing against a Minimum Acceptable Rate of Return (MARR) or "hurdle rate," which for Federal analyses is the discount rate, as well as against yields on other investments. If the computed IRR exceeds the MARR or hurdle rate the investment is deemed economically worthwhile. Other things being equal, the higher the IRR the more economically worthwhile the investment.[9]

Figure I-2. Economic Performance Measures

- Net Present Value Benefits (NPV): time-adjusted benefits minus costs

$$NPV = SB_{PV} - (SC_{PV} + SI_{PV})$$

where SB_{PV} = sum of present value benefits; SC_{PV} = sum of present value non-investment cost; and SI_{PV} = present value investment cost

- Benefit-to-Cost Ratio: time-adjusted benefits (net of time-adjusted non-investment costs) divided by time-adjusted investment cost

$$B/C = (SB_{PV} - SC_{PV}) / SI_{PV}$$

- Internal Rate of Return (IRR): the solution interest rate (i) that equates the values of the streams of benefits and costs over time

$$SB_{(i)} = (SC_{(i)} + SI_{(i)})$$

Source: TIA Consulting, Inc.

[8] The ratio is sensitive to the placement of costs. Investment costs are to be placed in the denominator; operating and maintenance costs are to be subtracted from benefits in the numerator. Note that moving these costs to the denominator will change the value of the ratio.

[9] When either the B/C ratio or the IRR are used to design or size projects, these measures must be applied incrementally, because the mutually exclusive alternative with the highest B/C or IRR computed on total benefits and costs is not necessarily the one that yields the highest net benefits. However, choosing among competing designs and sizes is not the point of these benefit-cost impact studies, and the need for incremental or marginal analysis is not expected to arise.

Unlike the previous two measures, the discount rate is not used directly in the IRR calculation. Rather, the IRR is solved for by substituting an interest rate with unknown value in place of the discount rate in discounting formulas and solving for the rate for which time-adjusted benefits equal costs, i.e., for which NPV is zero.[10]

Inclusion of Other Effects

There may be economic effects that are not feasibly captured in dollar terms. If so, these are omitted in the economic performance measures. However, it has been commonly recognized in benefit-cost analysis that if other effects are potentially important to decision making, they should not be ignored, and, at a minimum, should be treated qualitatively.

Yet, because the attention of benefit-cost studies is ultimately on the economic performance measures, omitted effects are often given less attention than they deserve. Thus, evaluators have in past studies attempted to express various important effects (not usually considered economic) in monetary terms, and to include the results in computing NPV, BCR, and IRR. For example, the value of a statistical life based on willingness-to-pay was used by Ruegg and Fuller in 1984 in a benefit-cost study of fire-suppression technology, and by Butry, Brown, and Fuller in a related 2007 study. Studies of highway safety, consumer product safety, and medical treatments have variously included estimated values of life and injury or imputed such values, or have used a cost-utility analysis and quality-adjusted life years to avoid placing financial values on life. Evaluators have also in past studies assigned monetary values to a variety of intangible effects such as environment, view, and business reputation, depending on the topic of major importance. However, these approaches have been largely piecemeal, non-systematic, and controversial.

This Guide seeks to include the treatment of important, difficult-to measure, effects using a systematic, non-controversial approach, as explained below in section I.3, *Special Features of the EERE Benefit-Cost Approach.*

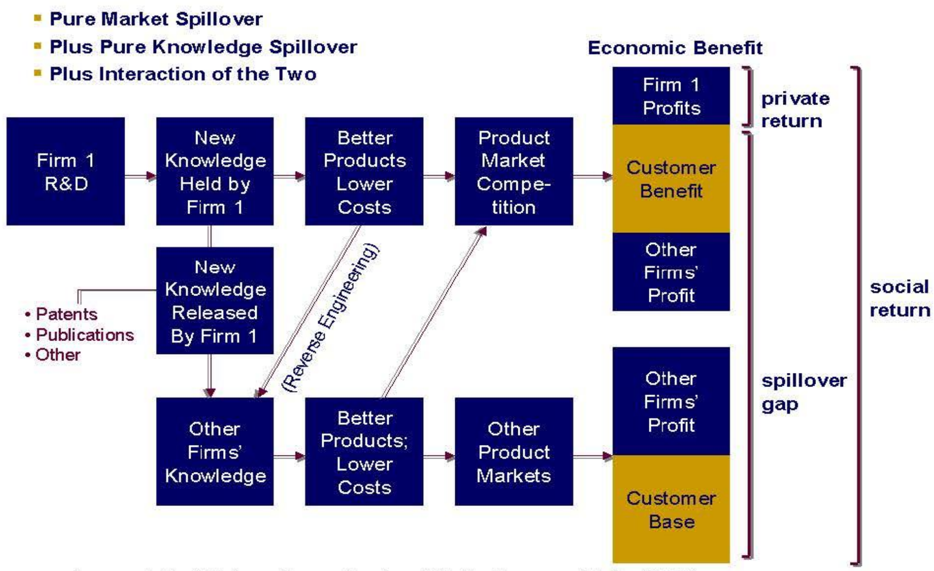
Federal versus Private Company Benefit-Cost Analysis

Major differences between a benefit-cost analysis performed for a company and one performed for the Federal government are perspective/scope and treatment of taxes. Regarding perspective/scope, a company typically counts as benefits and costs the cash inflows and outflows it directly realizes as a result of its investment (i.e., the *"private rate of return"*). In contrast, the Federal government typically counts all benefits and costs to the nation resulting from its action, regardless of who experiences them (i.e., the *"social rate of return" which encompasses both private returns and spillover returns*). Figure I-3 depicts in simplistic terms how private return and market and knowledge spillovers combine to produce social return.

[10] There are computer algorithms available for solving for the IRR. It can also be solved manually by a series of iterations, in which trial values of i are used until a solution value is found.

Thus, Firm 1 invests in R&D, and realizes higher profits, due, say, to now having better products and lower production costs. But the situation is dynamic, and other firms may gain some of the resulting knowledge ("knowledge spillovers"), and they may compete with Firm 1 in its markets driving down prices and allowing consumers to benefit from better products at lower prices ("market spillovers"). In addition, some of these knowledge-acquiring firms may use it to produce other kinds of better or lower cost products in other markets. Some of these other benefits are captured by the producing companies; in competitive markets, some will "spill over" to consumers. Thus there is a private return to Firm 1, but there are also effects from Firm 1's actions that "spillover" to others—both to other firms and to consumers. The overall effect is the "social return."

Figure I-3. Private Return and Spillovers Combine to Produce Social Return



Source: Jaffe (1996), as discussed and modified by Ruegg and Feller (2003)

If a Federal government investment contributes to development of an improved technology, a benefit-cost analysis to assess if the Federal investment was worthwhile would take into account the net effect across all establishments and people in the nation attributed to the Federal investment. Thus, a Federal benefit-cost analysis, with its focus on social returns, typically has a much broader perspective and scope of coverage than a private-company analysis with its focus only on its own returns. An analysis of social returns is therefore typically much more complex and difficult to perform than a private-company analysis.

With regard to treatment of taxation effects, a company analysis and a Federal analysis also differ, however, this difference tends not to be as major as the differences of

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perspective and scope. A company typically wants to know its after-tax bottom-line return. In contrast, Federal government benefit-cost analysis is typically performed on a before-tax basis. A before-tax estimation is done because government is the recipient of Federal taxes collected, and other forms of taxes are typically not separately assessed in Federal benefit-cost analysis--unless, of course, a study is specifically aimed at assessment of the effect of specific taxes or tax incentives.

It should also be noted that it is often not necessary for a Federal benefit-cost study to estimate fully the social benefits and costs associated with a new technology to achieve its evaluation purpose. For example, to estimate if a public R&D investment in a given technology area has been worthwhile, the required analysis is of the public returns, compared to the public R& D investment cost, rather than total social benefits of having the technology versus its total social costs. To estimate the return on public investment in a specific set of wind energy technologies, for instance, it is only necessary to compute the **change** in social benefits from wind energy technologies attributed to the public investment. That is, the computation does not require that total social benefits from having all wind energy technology be computed and compared against the total social costs—a much larger task.

Use of the Mansfield's Model as a Unifying Framework for the Valuation of Economic Benefits

A model developed and applied by Professors Griliches and Mansfield, and since applied by others, has proven a useful framework for estimating social and private returns from investments in new technology.[11] Mansfield applied the model to assess social benefits of private-sector industrial innovations, finding the estimated social rate of return for a group of selected industry innovations to be substantially higher than the private rate. He concluded that there may be a substantial "spillover gap" between private and social rates of return, whereby social rates of return exceed private returns. An implication is that private R&D investment decisions, which do not take into account spillover effects, will tend to result in less investment in R&D than is optimal from the standpoint of society at large.

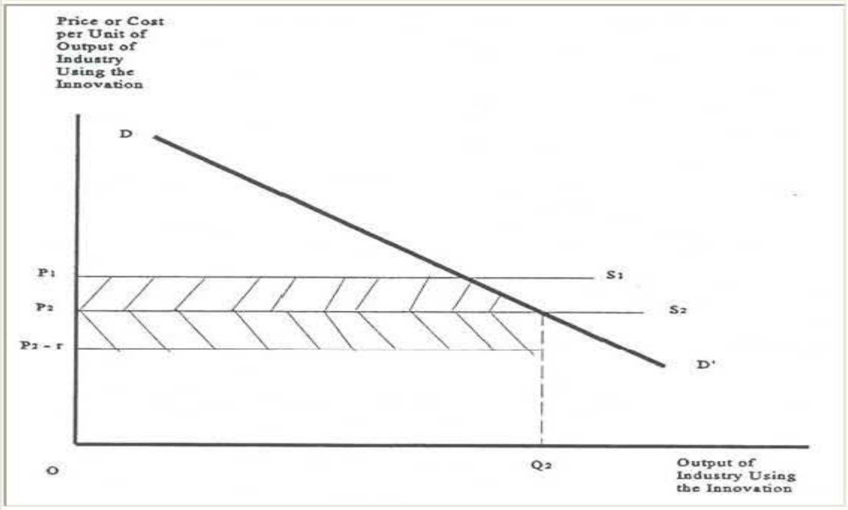
The "Griliches/Mansfield Model" has subsequently been applied to the analysis of Federal R&D investments. The model, which is well known to economists/practitioners of social benefit-cost analyses, is expected to serve as a theoretical anchor and unifying framework for the valuation of economic benefits in the EERE retrospective benefit-cost studies addressed by this Guide.

The simplified representation in Figure I-4 of the Griliches/Mansfield model serves to illustrate the valuation approach.

[11] Griliches (1958), E. Mansfield, J. Rapoport, A. Romeo, S. Wagner, and G. Beardsley (1977); Foster Associates, (1978); Nathan Associates (1978), , "Net Rates of Return on Innovations," Report to the National Science Foundation, July 1978.

Suppose that an innovation results in a new product used by firms that reduces costs of the industry using the innovation. The social benefits from the innovation can be measured by the profits of the innovator plus the benefits to consumers of the goods produced by the industry using the cost-reducing innovation. To the extent that the innovation is adopted (or adapted) in other applications, a similar approach could be taken in each application and the total social benefits (less costs) aggregated. Professor Mansfield acknowledged that the calculations are not this simple, but indicated that the basic model conveys the spirit of the analysis.[12]

Figure I-4 Griliches/Mansfield Model of Social Benefits from an Innovation that Reduces the Cost of Producing a Good Sold



Source: Edwin Mansfield, *Estimating Social and Private Returns from Innovations Based on the Advanced Technology,* 1996.

With reference to Figure I-4, DD' depicts a demand curve for the goods using the cost-reducing innovation. The horizontal supply curve labeled S1 reflects the pre-innovation supply of the goods, and P1 indicates the pre-innovation price paid by consumers. The horizontal supply curve labeled S2 reflects the post-innovation shift downward of the supply curve due to decreases in production costs, and P2 indicates the new price that consumers will pay. The top-hatched area indicates the gain in consumer surplus, due to

[12] Professor Mansfield was engaged by the Advanced Technology Program to extend his model to apply in benefit-cost studies of ATP-funded innovations. This brief description of his model is from a preliminary planning report for that effort. Edwin Mansfield, *Estimating Social and Private Returns from Innovations Based on the Advanced Technology Program: Problems and Opportunities*, National Institute of Standards and Technology, GCR 99-780, January 1996 (Available on-line at www.atp.nist.gov/eao/gcr99-780/contents.htm).

the innovation. It is the excess of what consumers would have been willing to have paid for the new quantity versus what they actually had to pay, summed over all purchases.

How far downward the supply curve will shift depends, of course, on the effect of the innovation, the pricing policy of the innovator, and the competitive structure of the industry sector. If the industry sector is characterized by little competition, the innovator may be able to hold the product prices relatively unchanged, such that the supply curve shifts little or none. However, if the industry sector using the innovation is competitive, it is expected that the innovator will lower the price for its new product as others enter with competing products.

The social benefits from the innovation can be measured by the sum of the two cross-hatched areas in Figure I-4. The top cross-hatched area is the consumer surplus due to the lower price (P2 rather than Pl) resulting from the use of the innovation. In addition, there is a resource saving, and a corresponding increase in output elsewhere in the economy, due to the fact that the resource costs of producing the good using the innovation are less than P2 Q2. Instead, they are P2 Q2 minus the profits of the innovator from the innovation (r), the latter being merely a transfer from the producers of the good using the innovation to the innovator. Thus, besides the consumer surplus arising from the price reduction, there is a resource saving amounting to the profits of the innovator. For example, suppose the innovator reaps a $100 million profit from its innovation. This means that P2 Q2 is an over-estimate of the value of the resources used by the industry, in the amount of $100 million; the amount the industry pays the innovator in profits. Recall that this payment to the innovator is not in exchange for resources; rather, it is a transfer of profit to the innovator.

Two adjustments are needed in the estimate corresponding to the lower shaded area in Figure I-4. First, if the innovation replaces another product, the resource saving cited above does not equal the profits of the innovator. Instead it equals these profits less those that would have been made (by the innovator and/or other firms) if the innovation had not occurred and the displaced product had been used instead. Second, if other firms imitate the innovator and begin selling the innovation to the industry that uses it, their profits from the sale of the innovation must be added to those of the innovator to get a full measure of the extent of the resource saving due to the innovation.

Using this model, an estimate can be made of the social benefit in each period from the investment in a given innovation. For each innovation, the top shaded area in Figure I-4 equals,

$$(P1 - P2)\ Q2\ (1 - 1/2\ Kn) \qquad (1)$$

where K = (P1 - P2)/P2, and n is the price elasticity of demand (in absolute value) of the product of the industry using the innovation.

To estimate P1 - P2, Mansfield's approach was to obtain as much information as possible on the size of the unit cost reduction due to the innovation. To obtain a reasonably reliable estimate of (P1 - P2), Mansfield conducted interviews with executives of the innovating firm, executives of a sample of firms using the innovation, and reviewed reports and studies made by these firms for internal purposes. And with the estimate of (P1 - P2), it was then possible to compute K. Q2 was generally available from published records. Rough estimates of n were obtained from published studies and from the firms. Since K was generally very small, the results were generally not very sensitive to errors in n.

Indeed, Mansfield concluded that the expression in equation (1) could be approximated well in most cases by (P1 - P2) Q2, which is the total savings to consumers due to the lower price if they buy Q2 units of the product of the industry using the innovation. This latter point has been helpful in the practical application of Mansfield's model.

To use the Griliches/Mansfield model for estimating net benefits from a public-sector innovation, the approach is to estimate social benefits as the stream of consumer and producer surplus resulting from an innovation. The counterfactual case is assumed to be the technology and associated demand and supply situation that existed just prior to the innovation and that would have existed without the innovation. The social cost is the combined public and private R&D and related costs over time incurred for the purpose of innovation. Public benefit is the part of social benefits attributed to the public investment, plus any reductions in realized total social costs compared with counterfactual total social costs. Public investment cost is the cost of the public program.

Note that the Mansfield approach includes market spillover effects which occur as others in the same industry as the innovator, within competitive markets, use the innovator's knowledge to imitate the innovation and drive down prices to consumers. Not included in the simplistic depiction of Figure I-4 are effects that occur as firms outside the innovator's industry draw from the same knowledge base to produce other goods and services in other industries. Also not included are non-economic effects, such as environmental, energy security effects, and the more general effects of an enhanced knowledge base on the capacity of organizations to innovate in other areas. These later effects are addressed explicitly by the EERE approach.

I.3 Special Features of the EERE Benefit-Cost Approach

This section briefly describes the special features of the EERE benefit-cost approach. They are:

- Use of a cluster approach
- Extension of the benefits evaluation to account systematically for multiple categories of benefits – energy, labor, and other resource effects, environment, energy security, and knowledge diffusion
- Improved characterization of the next-best alternative
- Detailed analysis of attribution of benefits

- Focus only on retrospective, empirically-based benefits and costs
- Exclusion of treatment of employment and regional effects
- Qualitative/quantitative treatment of international effects only if important to the assessment of public benefits
- Use of sensitivity analysis

Each of these features is briefly described below.

Cluster Approach

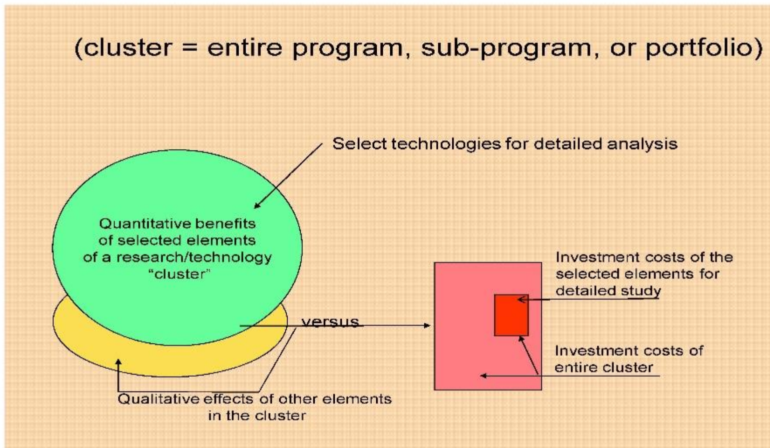
EERE's approach extends the analysis to "clusters" or portfolios of projects, with a cluster consisting of an entire program or subprogram or other grouping of similar technologies or related projects. Selected individual technologies within a cluster are evaluated in detail; remaining technologies within the cluster are treated qualitatively. Benefits of the selected technologies may be compared against their own costs, but, more importantly, they are compared against the investment cost of the entire cluster, as illustrated in Figure I-5. The resulting economic performance measures of benefits against cluster costs provide a minimum rate of return on EERE's investment in the program cluster – a lower bound estimate.[13]

The EERE cluster approach tends to be cost-effective because it enables the evaluation to be focused on a relatively few projects in a larger R&D portfolio (project or subprogram portfolio), while enabling broader conclusions to be drawn about an entire program or a subprogram. Furthermore, the approach works well for high-risk R&D programs where a few projects tend to be the big winners, but investment in an array of projects is necessary to find the few that will turn out to be highly successful.

From the standpoint of a program manager, cluster analysis offers the possibility of presenting a strong evaluative position. The strong position is that of being able to demonstrate that benefits from only a few elements in a larger cluster more than offset all program cluster investment costs, while additional elements in the cluster also hold promise of additional benefits or, at a minimum, offer little threat of offsetting effects.

[13] As noted earlier, the use of benefit-cost analysis applied to technology clusters was pioneered by the U.S. Advanced Technology Program (ATP) in the early 2000s.

Figure I-5. Illustration of Benefits versus Costs in EERE Benefit-Cluster Approach



Source: Rosalie Ruegg, TIA Consulting, Inc.

Multiple Categories of Benefits

The EERE approach extends the comprehensiveness of the benefit-cost analysis by credibly accounting for multiple categories of benefits. EERE assessment of benefits includes the following four categories, pushing coverage substantially beyond traditional benefit-cost studies:

- **Energy and Economic Benefits** — taking into account all affected resources in the economy, including energy, labor, and other resource effects estimated in dollars, and following the general approach of the Griliches/Mansfield model. Economic benefits are increases in the value of goods and services in the economy. Technological advancement is one way to increase economic benefits. This occurs by improving the performance of existing goods and services and/or reducing their costs, and by developing novel goods and services that provide desired new capabilities and experiences with economic value.

  Energy effects are part of economic benefits, but they are also treated separately because energy is the focus of the EERE programs. Energy effects are assessed in terms of energy saved, or MW capacity generated by renewable in lieu of fossil-based generation.

- **Environmental Benefits** — greenhouse gases, and public health effects from reductions in air emissions including mortality and morbidity effects and dollars of health cost avoidance calculated using EPA's COBRA Model; plus any notable other environmental effects (e.g., water discharges, land resource use, and solid waste generation).

- **Energy Security Benefits** — expressed as imported barrels of oil equivalent units avoided for displaced fossil fuels and also billions of gallons of gasoline equivalent (GGE) and millions of cubic feet of natural gas;[14] and includes qualitative identification of notable effects on the security of energy infrastructure.

- **Knowledge Benefits** — creation and dissemination effects of knowledge outputs of the cluster as indicated by chiefly by patent and publication counts and citation analysis, together with treatment of other knowledge creation and dissemination effects as feasible.

Improved Characterization of the Next-Best Alternative

The benefits of a new or improved technology are assessed in comparison with the next best alternative, i.e., the best choice that could be made in lieu of choosing the new technology. The next-best alternative is also often called the "defender technology." The performance of the defender technology provides a baseline against which to take the performance differences afforded by the new or improved technology. If the defender technology would likely have been improved over time if not displaced by the new or improved technology, estimation of the baseline may require dynamic modeling. Incorrect identification of the defender technology can result in substantial errors in benefit estimation. To support sound selection of the defender technology, Part II of the Guide provides examples of conditions that will influence its determination.

Detailed Attribution of Benefits

Assigning attribution for assessed benefits is a particularly key step in the EERE approach. The observation of positive effects does not necessarily mean that the EERE R&D cluster investment was responsible for generating the benefits. Other potentially causal factors must be taken into account and eliminated as rival explanations for benefits generation.

In contrast to the EERE attention to attribution, benefit-cost analyses often simply assume that all observed benefits are attributed to the subject investment. Alternatively, they use a simple rule-of-thumb. Rather than rely on a simple rule-of-thumb approach to attribution, the evaluation approach presented by this Guide promotes a detailed, case-by-case approach to assessing attribution.

To focus attention on the detailed attribution of benefits at the various stages of technology development, the matrix in Figure I-6 is provided to guide the evaluator in the comprehensive assessment of attribution. The tabular framework helps map attribution to

[14] Monetary value was not applied to barrels of oil equivalent units because the methodology is considered to require further development.

Figure I-6. Detailed Assessment of Benefits Attribution

A Matrix for Assessing Attribution by Technology Stage

Categories of Information Needed for Additionality Assessment	Technology Timeline (Stage of Research, Development, and Commercialization)→					
	Preliminary & detailed investigation	Develop components	Develop system	Validate/ demonstrate	Commer-cialize	Market Adoption
History of the technology						
What DOE Did						
What Others Did (Rival Explanations—Private Sector and Other Nations)						
What Others Did (Rival Explanations –US & State Government)						
The DOE Effect						
Description of DOE Influence And its strength						
Basis of evidence of influence						

the technology timeline to show when each identified effect is estimated to have occurred, to identify and eliminate rival explanations, and to indicate the range of attribution to the R&D program.

Supporting evidence of attribution is provided by the publication and patent analysis that is done to assess knowledge benefits. The knowledge benefits assessment demonstrates quantitatively and qualitatively the linkages between the publicly funded R&D and downstream commercial activities.

Only Retrospective, Empirically Based Benefits and Costs are Included

The measures for each category of benefits are to be derived fully from retrospective analysis, rather than life-cycle or prospective analysis. Only the benefits achieved, and costs incurred, are taken into account; no projections are included. The impact results quantified are thus also <u>fully retrospective.</u>

Quantification of monetary value of some externalities (e.g., CO_2, energy security) are excluded because current approaches to estimating for damage costs do not at this time support an acceptable level of confidence.

Exclusion of Employment Effects and Regional and International Effects

Employment Effects

Beyond the inclusion of labor costs as a resource that may figure in economic benefit-cost analysis, the Guide includes no specific requirement for the treatment of employment effects, such as estimate of numbers of jobs created or retained, or salary effects.

There are several reasons for this decision to omit the treatment of employment effects. One reason for the omission is the fact that many of the past investments treated in retrospective evaluations were done under conditions approaching full employment—they were not planned or implemented with a specific goal of achieving employment. Under conditions of national full employment, the assumption was that jobs added by one investment would be offset by transfers from jobs elsewhere, rather than resulting in net job gains.

More recently, with unemployment a pressing issue and energy projects part of the Federal economic stimulus package, employment effects of energy projects have gained attention. With employment goals for energy investments, the explicit treatment of employment effects in terms of number of jobs created or retained and salary effects may be added to future retrospective benefit-cost studies of energy projects. If this happens, it will be noted in the release of an Addendum to this Guide.

Regional Effects

Aside from specific regional development efforts taken at the Federal level, regional shifts in economic activity are generally not separately included in Federal evaluations. Rather, Federal evaluations typically are focused on national economic effects, and regional shifts are assumed to have a neutral national effect. Thus, regional effects are not called out for separate treatment in the EERE benefit-cost studies.

International Effects

There is little precedence for treating international effects in Federal benefit-cost studies. Also, there is the more immediate concern that requiring their treatment would exceed the resource and time constraints of project funding levels.

In the case of certain technologies, however, a treatment of international effects will be needed to understand national impacts. For example, it is difficult to understand returns to the U.S. public investment in NiMH batteries without having at least some understanding of the development and interrelationships of R&D, innovation, battery commercialization, and markets for battery applications in different parts of the world.

Thus, evaluators of EERE benefit-cost studies are encouraged to provide an overview of international effects, as well as a more detailed assessment of international developments when they are critical to estimating and understanding national benefits in a given technology area.

Use of Sensitivity Analysis

Even for a retrospective, empirically based evaluation, there will be uncertainties about assumptions, data, and, therefore, results. The EERE approach emphasizes the identification of areas of uncertainty and the use of sensitivity analysis to reveal how changes in uncertain values of critical inputs will affect overall estimates of benefits. [15] Examples of input variables that might be subjected to sensitivity analysis are the quantity of energy saved or the degree of attribution of benefits to the program cluster.

[15] Sensitivity analysis is an approach widely used in economic impact studies to acknowledge that there are uncertainties, and to test the effect of changing one or more key input values for which there is uncertainty. When the probabilities that input values differ from "best-guess" estimates are known, risk assessment can be used--instead of sensitivity analysis--to assess the risk exposure inherent in an investment decision. Risk assessment techniques include expected value analysis, decision analysis, simulation analysis, and other techniques described by Ruegg (1996). Risk assessment techniques may also be used in the EERE approach, but are not required. For more on sensitivity analysis, see Saltelli, Chan, and Scott (2000) and Marshall (1996).

Part II. Step-by-Step Guide

Overview of a Step-by-Step Approach

An overview of the step-by-step flow diagram of the EERE approach to retrospective benefit-cost cluster analysis is given in Figure II-1.

It should be emphasized that depicting the evaluation approach as a series of sequential steps does not mean that the process is either linear or formulaic. Conducting a successful study requires an evaluator experienced in both the art and science of benefit-cost analysis, able to capture complex and multiple direct and indirect effects of a public investment using creativity and a variety of techniques within the organization of a step-wise approach, and aware of the dynamic nature of the process.

Part II of the Guide follows the logic of the diagram in Figure II-1. Key process steps are indicated in the text by the symbol "►". Examples from the first-round of 2010 studies are selectively presented to illustrate key steps and are indicated in the text by the symbol ◙.

Figure II-1. Major Steps in the Evaluation Process

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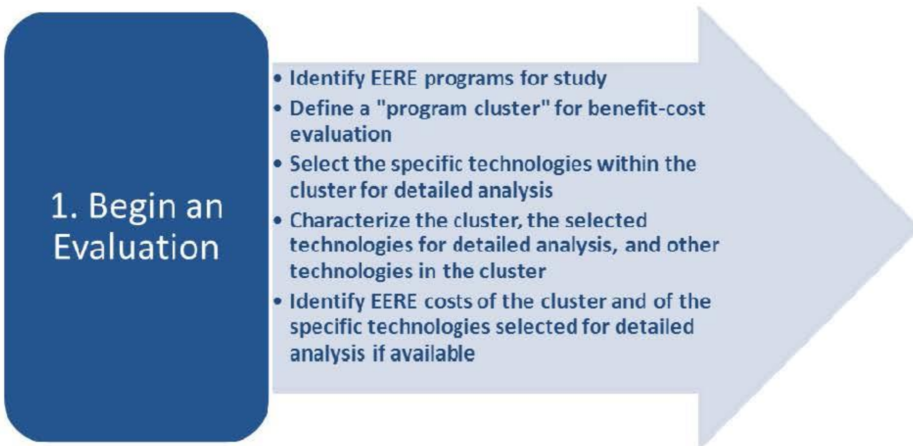
1. Begin an Evaluation



► Identify EERE programs for study

A starting point for benefit-cost evaluation is determining which EERE program to evaluate. This likely may be done internally by the EERE staff with the subsequent issue of an EERE Request for Proposal (RFP), or it may be done jointly by a contracted evaluator and EERE staff. The identification of a program cluster follows this initial step.

In general, an EERE program that could benefit from participating in an impact evaluation study conducted according to this Guide would be --

- One for which return on investment is currently not known; or
- One that was previously evaluated in the 2001 NRC study but,
  - had shown no significant realized economic return on R&D investment, in part because accrued market value had not been established for its commercialized technologies during the period of the NRC study, or
  - had successfully commercialized technologies that were excluded from a previous benefit-cost study, or
- One previously evaluated but requires an update (e.g., 2 to 5 years later), or
- One that had performed benefit-cost calculations using an alternative approach not consistent with the EERE approach presented in this Guide.

► Define a "program cluster" for benefit-cost evaluation

Evaluators are expected to work collaboratively with Program staff to define a program cluster for benefit-cost analysis. In the event that they are responding to an EERE Request for Proposal (RFP), the EERE Program staff will typically have identified the program cluster for study in advance.

The program cluster identified for study may be defined as:

1) An entire program's portfolio of related projects/activities,
2) A comprehensive collection of related projects/activities with a shared objective that forms a subprogram or category within a larger program, or
3) A set of related projects/activities that cut across several programs but share a common feature that makes it reasonable and desirable to group them.

Thus, the program cluster may comprise an entire EERE Program, a Sub-program, or some other grouping or portfolio of projects or technologies that share common attributes.

The step of "defining a program cluster" is to be implemented in close coordination with "selecting specific technologies within the cluster" and "characterizing the cluster" – described below. This is because often preliminary explorations will need to be done to assess the feasibility of a given program cluster for study. Preliminary explorations would entail taking note of the market uptake of candidate technologies, preliminarily considering their likely impacts, and assessing data availability and other feasibility conditions for studying the program cluster.

In a 2010 study for DOE's Advanced Combustion Engine R&D (ACE R&D) the program cluster was taken as the ACE research effort. This included R&D for Laser Diagnostics and Optical Engine Technologies, Combustion Modeling, Combustion and Emission Control, and Solid State Energy Conversion. The ACE R&D Sub-Program is one of eight sub-programs within a larger DOE Vehicle Technologies Program. In the ACE R&D benefits-cost study, the program cluster was the entire R&D portfolio comprising R&D in the ACE subprogram.

► Select specific technologies within the program cluster for detailed analysis

After the program cluster has been identified, the next step is to select a few technologies within the cluster for detailed benefit-cost analyses (again in collaboration with EERE Program staff or as specified by the RFP). The technologies selected for detailed study could be, for example:

- A whole system (e.g., an advanced wind turbine or a geothermal plant); or
- A component of a larger system (e.g., blades for a wind turbine, or high temperature cement for a geothermal well application); or
- Infrastructure technology that enables a commercial advancement (e.g., new modeling capability, test results, or new designs); or
- A new or improved process (e.g., turbulence modeling for wind turbine inflow, or improved, faster deposition methods for solar PV thin films).

Because benefits of the few technologies in a cluster selected for detailed study will be compared against total EERE cluster costs, it makes sense—and, in fact, it is a feature of the approach—that those selected should be among the most successful in having achieved technical and commercial results prior to the study cut-off year[16] for the analysis. Further, it should be feasible to assess the benefits of those technologies selected.

Near term technologies not yet in commercial production are excluded from selection for detailed analysis. This exclusion extends to technologies that are in final development and demonstration stages at the time of selection, but which are not expected to have entered the market under currently projected economic, regulatory, and tax conditions until after the study cut-off year. This criterion is consistent with retrospective analysis which uses empirical data rather than projections. Also excluded from selection are technologies whose benefits cannot be feasibly measured. The example in Table II-1 lists clusters and technologies selected for detailed analysis within each cluster, from recently completed 2010 studies.

In the previous example, a subset of technology/ research areas from within the ACE R&D cluster was selected for examination in the benefit-cost assessment. The specific technologies within the cluster selected for detailed analysis were

- Laser diagnostic and optical engine technologies focused on heavy-duty diesel engines
- Combustion modeling –in particular KIVA modeling that simulates the fluid dynamics of combustion processes in internal combustion engines

Combustion and Emission Control and Solid State Energy Conversion were not included in the quantitative benefits analysis for the ACE R&D benefit-cost study, although the total cluster cost was accounted for in the analysis.

► Characterize the program cluster, the selected technologies for detailed analysis, and other technologies in the program cluster

For context, provide an overview of the program cluster to be studied, and of the technologies within the cluster selected for detailed analysis. Describe the objectives to be achieved by the program cluster, activities undertaken in support of these objectives, and how the technologies selected for detailed analysis have affected resource use. Explain why the program cluster and the technologies for detailed analysis were selected.

While the quantitative analysis centers on those several technologies selected for detailed analysis, it is important also to provide at a minimum a qualitative review of other elements in the program cluster. The aim is to give a sense of the likely overall impact on program cluster net benefits of these other elements within the cluster. Is there reason to believe that these other elements will not offset any positive effects of the selected technologies? Is there reason to believe they will provide additional benefits?

[16] For each of the four benefit-cost studies completed in 2010, the study cut-off year was end of 2008. The cut-off year will vary, depending on the year a study is initiated and availability of data for the analysis.

Table II-1. Program Clusters and Selected Technologies for Detailed Analysis within Each Cluster, 2010 EERE Benefit-Cost Studies

Four Program Clusters (2010 Studies)	Technologies within Each Cluster Selected for Detailed Analysis (2010 Studies)
Geothermal Technologies Program	• Polycrystalline diamond compact (PDC) drill bits • Binary cycle power plant technology • TOUGH series of reservoir models • High-temperature geothermal well cements
Wind Energy Program	• Wind turbulence models • The unsteady aerodynamic experiment to acquire accurate aerodynamic and structural measurements • Turbine blade material characterization and analytical modeling work • Wind turbine component demonstration programs
Photovoltaic (PV) Energy Subprogram of the Solar Energy Technology Program	• Flat-Plate Solar Array project • PV Manufacturing Technology Project • Thin-Film PV Partnerships
Advanced Combustion Engine R&D Subprogram of the Vehicle Technologies Program	• Laser diagnostic and optical engine technologies focused on heavy-duty diesel engines • Combustion modeling --in particular KIVA modeling that simulates the fluid dynamics of combustion processes in internal combustion engines

► Identify EERE costs of the program cluster and, if possible, of the specific technologies selected for detailed analysis

Cluster costs are the cost of the program or subprogram or other portfolio chosen for study. Thus, costs of all projects within the cluster are to be included; nothing within the cluster scope is to be left out of cluster costs.

Total program and subprogram costs should be available for past years from the program. However, costs broken out for parts of subprograms or for individual technologies within a cluster may be less readily available. Because total cluster costs are essential to computation of the desired economic performance metrics, obtaining them is imperative. As soon as the cluster is defined, program staff should take steps to provide cost data for the relevant cluster to the evaluators, and the evaluators should request the cost data from the program.

This is a critical step in the entire process. It requires consistency of program budgeting practices over time or the regrouping of subprograms by those knowledgeable of past practices and adjustments to budget categories to provide the required cluster cost data.

It is program's responsibility to provide the necessary cluster data to the evaluators. It is evaluator's responsibility to bring this requirement to the attention of program staff.

Cluster costs should be presented year-by-year over the entire period of the program's investment. Costs can be expressed in actual dollars at the outset, but are to be converted to yearly inflation-adjusted constant dollars for the designated year.[17]

At a minimum, evaluators are asked to assemble the program investment costs data for the entire program and obtain data for the program cluster (or subprogram), as well. For example, the entire DOE Wind Energy Program investment ($1.7 billion, $2008 inflation adjusted), as well as the R&D costs of the selected infrastructure technologies ($1.2 billion) was assembled for the Wind benefit-cost study. For the Wind Energy Program example, the time series of costs of the program cluster versus the total program cost over the historical period 1976 to 2008 are given in Table II-2.

> In a 2010 Wind Energy R&D Benefit-Cost study, the cluster and selected technologies were characterized as infrastructure technologies –
>
> - Wind turbulence models
> - The unsteady aerodynamic experiment to acquire accurate aerodynamic and structural measurements
> - Turbine blade material characterization and analytical modeling work
> - Wind turbine component demonstration programs.
>
> In the benefit-cost study, the selected group of infrastructure technologies were treated as a group of infrastructure technologies, rather than separately.
>
> Public investment in these infrastructure technologies represented only a portion of the total public investment of the Wind Energy Program – i.e., 70% of its total historical budget.

Economic performance measures are calculated and reported based on both the entire program and the cluster costs. If the costs of the individual technologies selected for study are separately identified, the evaluators are instructed to also calculate net economic benefits based on the investment relevant to the selected technologies examined. At a minimum, they are asked to report calculated results for the total cluster investment.

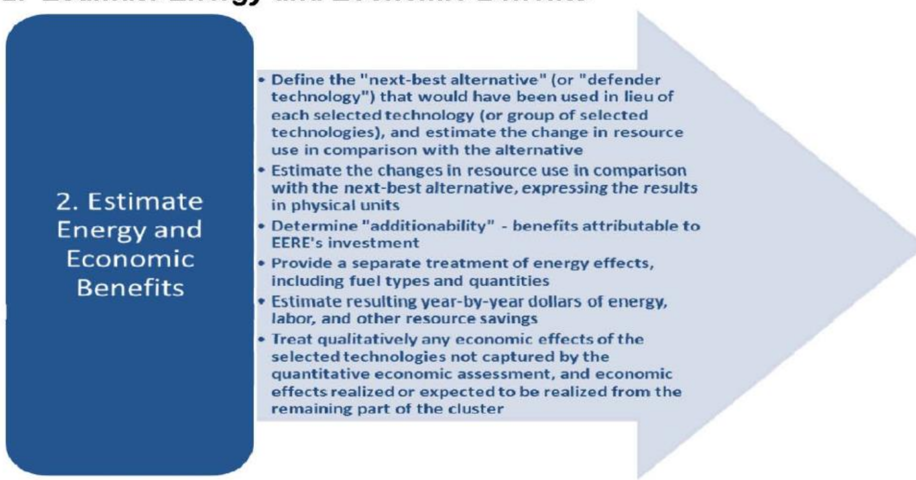
[17] See addendum pertaining to key dates and other updated information applicable to current studies.

Table II-2. Investment Costs in the Wind Energy Program (the Benefit-Cost Study Cluster) and Investment Costs for Selected Technologies within the Cluster

Year	Investments in Selected Infrastructure Technologies Nominal (Thousand Dollars)	Total Wind Energy Program Investments Nominal (Thousand Dollars)	Inflation Adjusted Investments in Selected Technologies 2008 Dollars (Thousand Dollars)	Inflation Adjusted Total Wind Energy Program Investments 2008 Dollars (Thousand Dollars)
	(1)	**(2)**	**(3)**	**(4)**
1976		14,403		44,027
1977		20,500		58,910
1978	34,470	35,300	92,560	94,788
1979	58,155	59,555	144,166	147,636
1980	56,254	60,555	127,801	137,572
1981	76,087	77,500	158,050	160,985
1982	37,700	38,400	73,807	75,178
1983	31,290	31,390	58,928	59,116
1984	26,367	26,367	47,860	47,860
1985	28,155	28,355	49,603	49,955
1986	12,536	24,786	21,608	42,723
1987	11,930	16,606	19,983	27,816
1988	8,064	8,464	13,059	13,707
1989	8,260	8,760	12,890	13,670
1990	8,498	8,687	12,768	13,052
1991	10,836	11,034	15,724	16,011
1992	21,082	21,282	29,883	30,167
1993	5,500	23,841	7,628	33,063
1994	9,334	29,151	12,678	39,593
1995	11,784	34,309	15,679	45,648
1996	16,830	31,420	21,974	41,023
1997	20,540	28,646	26,353	36,752
1998	17,301	32,128	21,949	40,759
1999	20,861	34,076	26,082	42,604
2000	17,219	31,734	21,072	38,835
2001	19,902	39,132	23,817	46,830
2002	21,731	38,211	25,592	44,999
2003	26,282	41,640	30,299	48,005
2004	26,188	39,803	29,358	44,621
2005	24,053	40,631	26,093	44,078
2006	17,276	38,333	18,150	40,273
2007	29,839	48,659	30,476	49,698
2008	22,643	49,034	22,643	49,034
Totals Investments	**736,967**	**1,072,692**	**1,238,531**	**1,718,989**

Source 1: Pelsoci (2010).

2. Estimate Energy and Economic Benefits



► Define the "next-best alternative" (or "defender technology") that would have been used in lieu of each selected technology (or group of selected technologies), and estimate the change in resource use in comparison with the alternative

The merits of the selected new technology are judged against the next best alternative, i.e., the best choice that could have been made in lieu of choosing the new technology. For a retrospective benefit-cost analysis, the next best alternative is defined by looking back to the time the investment decision was made for the new technology. That is, the next best technology at the time of the investment decision is not necessarily today's next best alternative. It is the choice **not** taken, and therefore it represents a counterfactual comparison.

In defining the next best, or defender technology, it is necessary to determine whether to use static or dynamic modeling. Based on what is known about the defender technology, it should be possible to determine whether it is more appropriate to model it as remaining constant or changing in performance over the period of comparison.

There is an element of judgment in the selection of the next best alternative—even for retrospective studies—but there are also determining factors to consider. One of these factors is whether the choice was constrained or unconstrained. For example, if use of a renewable energy system were required (say by a State requirement), investment in a renewable system would be compared against other renewable energy systems. Another factor is whether the technology was new to the world or an improvement over an existing system. If it was new to the world, it might be compared against the best alternative conventional technology. If the technology was an improvement over an existing system, it would likely be compared against the then best existing earlier system model. Table II-3 gives examples of the next-best alternatives identified for the four 2010 EERE Benefit-Cost Studies. The first column lists the study and technologies evaluated in detail, and the second column describes the next-best alternative.

Table II-3. Examples of Next-Best Alternatives Identified in 2010 Benefit-Cost Studies

Study (1)	Next-Best Alternative (2)
Advanced Combustion Engine (ACE) R&D Subprogram--laser and optical diagnostics	The state-of-the-art in diesel engine design and related brake thermal efficiency (BTE) that existed prior to 1995.
Geothermal R&D Program -- with 4 distinct technology cases	
1. Polycrystalline Diamond Compact (PDC) Drill Bits	Existing roller-bit drill technology.
2. Binary cycle power plant	For reservoir temperatures in the range of 150 to 190° C, flash cycle technology; and for temperatures in the range below 150° C, a coal power plant.
3. TOUGH series & related reservoir models	"Lumped parameter" models used before capabilities for detailed computer simulation of reservoirs were developed.
4. High-temperature geothermal well cements	Existing Portland cements.
Solar Photovoltaics R&D Subprogram--cSi modules and thin-film modules	Existing inferior crystalline silicon PV modules that would have been continued during the delayed introduction of the improved PV modules technology.
Wind Energy R&D Program--group of infrastructure technologies	Fewer, smaller, less reliable, less cost-competitive wind turbines with lower energy capture that would have been used during the delayed introduction of turbines based on the improved infrastructure technologies

It is a requirement that the benefit-cost study describe in the final report how the study has defined the next best alternative for each technology or group of technologies selected for detailed analysis, and what was the rationale.

► Estimate the changes in resource use in comparison with the next-best alternative, expressing the results in physical units

Perform year-by-year comparisons of the selected technology or group of technologies against the appropriate next best alternative to derive the differences in each type of affected resource stated in physical units. For example, what are the differences in quantities of energy consumption by type? What are the effects on labor requirements? What are the differences in purchase, installation, and maintenance costs? What are the differences in life expectancies?

These effects may differ among the selected technologies or groups of technologies and, if so, will require separate, individual comparisons with each next-best alternative.

It is at this stage that incremental energy savings and/or MW capacity is derived from differences in the performance characteristics of the selected technology and its next-best alternative. There are a variety of ways resource savings and associated energy/ fuel changes can be calculated, and the specific approach depends on the selected technology and available data. The calculation approach and results should be well documented in the study report.

The following are two examples for illustrative purposes --

(1) Wind Energy Benefit-Cost Study Example, Pelsoci (2010), where billions of kWh of electricity otherwise supplied by fossil fuel (calculated by type of fuel) were displaced by wind energy. (See Example A below)

(2) Advanced Combustion Engine (ACE) R&D Benefit-Cost Study Example, Link (2011), where billions of gallons of diesel fuel were saved. (See Example B and Figure II-2)

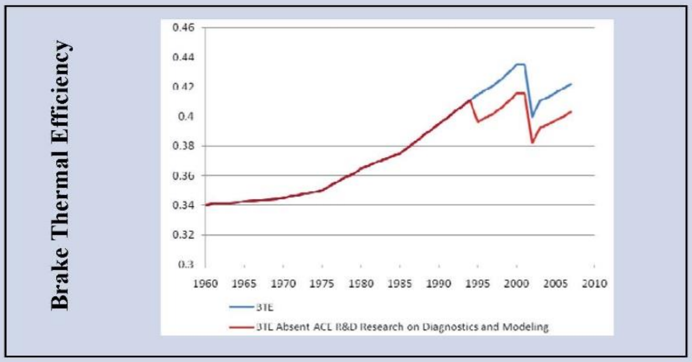
Example A: In the wind energy study, it was determined there was a six year acceleration effect, as determined from interviews with experts. Six was the mean value of the distribution of responses. This acceleration led to wind energy supplying 139.8 billion kWh that displaced electricity otherwise supplied by a fossil-fuel generation mix (where the mix is determined from the weighed fuel use of energy generation from fossil fuel mix of the States with the largest share of wind energy power):

- 61.5 billion kWh (i.e., 44% of total from wind) supplied by coal-fired generation
- 76.9 billion kWh (i.e., 55% of total from wind) supplied by natural gas-fired generation
- 1.4 billion kWh (i.e., 1% of total from wind) supplied by petroleum-fired generation.

This information provided the energy benefits estimate (e.g., power generation from wind) and also produced the inputs to the subsequent environmental emissions analysis for that benefit-cost study.

Example B: In the ACE R&D study, a statistical approach was adopted for the calculation of the fuel savings associated with miles per gallon (MPG) fuel economy improvements, where MPG improvements were linked to a 4.5% DOE-supported R&D improvement in Brake Thermal Efficiency (BTE) – shown in Figure II-2 (expert-derived counterfactual BTE). The change in MPG was statistically estimates (∂MPG / ∂BTE = 0.153) and the reduction in MPG absent the ACE R&D research was calculated. The calculated reduction in MPG was translated to reduced fuel consumption of 17.6 billion gallons of diesel fuel saved over the period 1995 to 2007.

Figure II-2. Trend in BTE over Time with Counterfactual



Source: Link (2010).

There may be multiple potential approaches to estimating energy benefits in benefit-cost studies. It is important to fully document the estimation approach used and the rationale.

► Determine "additionality" — benefits attributable to EERE's investment

The focus of the study is on estimating the return on EERE's investment, i.e., the "return on public investment." This entails delineating the part of the benefits from using the selected technologies in the cluster — in lieu of the next best alternative — that are attributable to the cluster investment. This step, often referred to by the program evaluation community as "assessing additionality," takes into account the possibility that to some extent development of the selected technologies may have occurred without the cluster investment.

This step to assess additionality—also counterfactual in nature—is an essential step in evaluating returns to the designated EERE cluster investment. It considers what likely would have happened without the EERE cluster investment. Only if the selected technologies would not have been developed and applied at all without the EERE cluster investment would the entire impact of the technology as computed against the next best alternative be appropriately attributed to the EERE cluster investment. In contrast, if it appears likely that the selected technology development and application would have happened in the same way, in the same timeframe without EERE as with it, then none of the benefits of the subject technologies can legitimately be attributed to the EERE cluster. These two cases represent the extremes, however, and the answer is more often found between these end points.

The assessments of additionality and next-best alternative are sometimes combined. However, the EERE approach calls for explicit treatment of each. Keep in mind that the purpose of the next-best-alternative component of the analysis is to determine the benefits of having the selected technologies versus not having them. In contrast, the additionality component of the analysis is to determine what share of the benefits of having the selected technologies is attributable to the R&D Program.

Table II-4 lists ways that Federal technology investments can cause change to occur. Ask what would have been different without the EERE cluster investment. Is it logical to expect that it gave rise to any of the effects listed in Table II-4? Are there other types of effects, not listed, that may have occurred? Identify and describe the expected additionality effects of the selected technology or group of technologies.

Table II-4. Ways Additionality Can Occur

Types of Effects	**Specific Examples of types of additionality**
Acceleration of technology development & commercialization	• Expanding R&D funding to achieve technical goals faster • Developing supporting research models, data, and designs that speed R&D • Lowering technical risk and removing other barriers to progress • Stimulating market awareness and receptivity
Improvement of technology performance characteristics	• Broadening the scope of R&D effort with larger goals • Increasing scale of R&D effort to take on more difficult and rewarding technical challenges
Reduction in the cost of a technology or the costs associated with its use	• Fostering of collaborative R&D to avoid investment redundancy • Provision of specialized facilities and services needed by an industry to make technical advances
Increase in the size of the market and amount of use of the technology	• Reduce barriers to market adoption, e.g., through demonstrations, information, training, and standards and certification activities • Increase access of U.S. firms to global markets

After identifying how the EERE's investment appears to have influenced change, estimate the extent of the additionality. Document and discuss the evidence that the identified additionality effects have occurred, using the tabular framework provided in Figure I-6 (See Part I). Designed to assist in organizing and reporting the analysis, the use of this framework will help to map attribution to the technology timeline to show when each identified effect is estimated to have occurred, to identify and eliminate rival explanations, and to indicate the range of attribution to the R&D program in terms of a percentage share of benefits generated by use of the selected technology or group of technologies.

The objective of the analysis of additionality is to assess and describe the degree of influence of the EERE in causing the estimated benefits of the selected technologies in comparison with their next best alternative, and to express the degree of influence in terms of a percentage share or preferably as a range of percentage shares (or, if appropriate, in terms of an acceleration effect, which may be expressed as a range of years). The following are suggested terms and associated percentage shares for representing different levels of influence:

- Overwhelming Influence (80-100%)
- Dominant (60-80%)
- Very Important (40-60%)
- Influential (20-40%)
- None to Minimal (0-20%)

Table II-5 gives an example for the Geothermal Program's PDC drill bit technology attribution analysis as summarized in the attribution matrix framework. The matrix serves as a framework and summary of more detailed attribution analysis findings documented in each study report.

The following conditions are expected to be met in attributing effects to the EERE R&D Program in the assessment of additionality:

- The postulated effect must make sense in terms of the R&D Program's logical theory (or logic model[18]) that relates program mission, strategy, activities, and outputs to longer term outcomes.
- If the Program has made a difference, there should be a corresponding time-order change whereby the Program's actions were taken prior to the observed changes and in the direction predicted with a sufficient lead-time to allow the changes to occur. This time order change should be documented, as illustrated in the examples below taken from the recently completed Solar energy benefit-cost study (O'Connor, et al, 2010).
- If there are potential rival explanations of the estimated benefits, these rival explanations need to be controlled for or separated from the effect of the selected technologies, such that it is the effect of the selected technologies that is identified in the additionality assessment and not other causes. Eliminating rival explanations is important because otherwise the benefits claimed for the selected technologies within the cluster could be due to other factors. There are two kinds of rival explanations pertaining to "what others did" (as noted in the attribution matrix framework Figure I-6 in Part I: (a) what other programs, private sector, and other nations did, and (b) what Federal and State Governments did.

[18] See McLaughlin and Jordan (2010).

Table II-5. An example of a completed attribution matrix

Categories of Information Needed for Additionality Assessment	Technology Timeline (Stage of Research, Development, and Commercialization)→					
	Preliminary & Detailed Investigation	**Develop Components**	**Develop System**	**Validate/Demonstrate**	**Commercialize**	**Market Adoption**
What DOE support of SNL and others did	▪ Study applicability of PDC drill bits to geothermal fields	▪ Worked on improving performance of drill bits ▪ Financed contracts and R&D efforts with GE	▪ Conducted research on drill mechanics and hydraulics ▪ Developed STRATAPAX and PDCWEAR, which helped place cutters on the drill bit	▪ Sponsored wear and friction tests ▪ Helped establish best practices ▪ Held workshops, sponsored publications and presentations	▪ DOE efforts helped commercialize PDC bits	▪ DOE scientists and engineers contracted with consortium of drill bit manufacturers to continue improving the performance of PDC drill bits
What others did (rival explanations)	▪ GE developed PDC in 1955 and first tested in the field 1973	▪ GE worked on DOE contracts	▪ GE used STRATAPAX to position cutters on drill bits ▪ Industry used PDCWEAR to create anti-whirl drill bits			
Driving/ restraining policies/ government forces (rival explanations)	▪ USGS study showed availability of geothermal fields around United States ▪ Oil crisis, U.S. government studied energy sources alternative to fossil fuels	▪ Oil crisis, U.S. government studied alternative energy sources to fossil fuels (including geothermal)			▪ Demand for oil went up, creating a demand for offshore drilling	▪ PDC bits became enabling technology for horizontal drilling widely used in offshore drilling ▪ Federal and State Tax Credits

Source: Gallaher, et al. (2010)

Table II-5 continued. An example of a completed attribution matrix

Categories of Information Needed for Additionality Assessment	Technology Timeline (Stage of Research, Development, and Commercialization)→					
	Preliminary & Detailed Investigation	Develop Components	Develop System	Validate/Demonstrate	Commercialize	Market Adoption
Description of DOE influence	▪ **Very Important (50%)** ▪ DOE efforts helped consider applications of costly PDC drill bit technology	▪ **Very Important (50%)** ▪ DOE supported the technology at the time when it seemed too costly and unreliable	▪ **Dominant (70%)** ▪ Developed analytical tools that helped advance the application of the technology ▪ Greatly improves bonding of cutters to drill bit	▪ **Dominant (70%)** ▪ DOE efforts helped show that it is possible to overcome the short-comings of PDC drill bit technology with engineering and research	▪ **Influential (25%)** ▪ DOE's efforts helped deliver PDC bits right before there was an increase in demand for a similar technology, which helped the adoption of PDC bits	▪ **Influential (25%)** ▪ DOE's expertise remained available for the industry to use in their own R&D efforts
Basis of evidence for influence	▪ Interviews with experts ▪ Articles ▪ Studies	▪ Interviews with experts ▪ Articles ▪ Studies	▪ Interviews with experts ▪ Articles ▪ Studies	▪ Interviews with experts ▪ Articles ▪ Studies	▪ Interviews with experts ▪ Articles ▪ Studies	▪ Interviews with experts ▪ Articles ▪ Studies
The DOE effect	▪ Accelerated technology entry	▪ Improved performance	▪ Improved performance ▪ Changed costs	▪ Improved performance		▪ Improved performance

Source: Gallaher, et al. (2010)

The period of analysis for the 2010 Solar benefits-cost study was 1975 to 2008. In that study, some of the time order change reported was:

- Module prices were reduced by a factor of 15, and efficiencies for modules in commercial production increased from about 5% to 10%.
- Reliability improvements sparked by testing at DOE's Flat-Plate Solar Array Project (FSA) allowed companies to offer at least 10-year warranties on modules and subsequently reached 20 years, whereas before FSA, warranties were nonexistent in the PV industry.
- During the period of DOE's Photovoltaic Manufacturing Technology (PVMaT) Project, direct costs of module manufacturing fell from $6.00/Wp (Watts peak) in 1992 to $2.92/Wp in 2005 (2008$).
- During the same period, MW capacity increased 18.5 times to 251 MW).

"What other programs, private sector, and other nations" did could include fuel prices; activities of other entities, including domestic and foreign companies and universities (who did not cost share with DOE), and foreign research laboratories. "What Federal and State governments did" would include requirements influencing investments in subject technologies). Examples of rival explanation factors related to Federal and State government actions:

- o Tax credits (e.g., Production Tax Credit (PTC), Investment Tax Credit (ITC)) and other technology market-supporting policies (such as low-interest loans for renewable technologies) that reduce the effective price of the subject technology.
- o Increases in fuel or other prices, which raise the cost of the next best alternative disproportionately.
- o Renewable Portfolio Standard (RPS)

- Discuss sources and degree of uncertainty regarding the percentage or range of percentages used to describe the degree of influence of the EERE R&D Program.

- Findings regarding additionality may differ within a given cluster study for each selected technology or group of technologies. Thus, the process of assessing additionality is expected to be repeated for each selected technology or technology group within a cluster. Attribution shares may range from 0% to 100%.

As part of the extensive and important effort to determine additionality, a study should employ multiple lines of data and carefully document the basis of evidence of influence. Multiple data could include, for example,

- Public record, patent citations
- Interviews with third parties

- Interviews with partners
- Interview with DOE or DOE lab staff
- R&D cost shares
- Other data source

Furthermore, any efforts to utilize interviews to assist with construction of counterfactual scenarios or determine attribution should seek to obtain necessary data from both DOE partners and third parties who are non-DOE partners. In addition, to the extent possible, a distribution of responses/ judgments from expert interviews should be documented and the mean value chosen as the point estimate further applied in the study for the purpose needed. The distribution of expert responses/ judgments should be documented and described in the study report.

After the additionality analysis has been completed, the attribution effect is applied to the energy and other resource savings found relative to the next-best-alternatives. This may entail taking a percentage share of the pre-attribution savings, or applying the effects of an acceleration to the pre-attribution savings.

►Provide a separate treatment of energy effects, including fuel types and quantities

While all resources are important to estimating economic benefits, there is a special data requirement for energy effects. Differences in the quantity of energy by type associated with technology selection not only figure into economic benefits, but also drive two of the other categories of benefits—environmental and energy security benefits. (Note that the quantity changes in fossil fuel consumption by type are carried forward to Steps 3 and 4.) Thus it is required that all energy effects by type and physical quantity be broken out for separate treatment.

►Estimate resulting year-by-year dollars of energy, labor, and other resource savings for each selected technology or group of technologies

Compile additional data needed to compute year-by-year economic resource savings, such as prices and labor rates.

Estimate year-by-year economic benefits for each selected technology or group of technologies, taking into account the combined effect of the next-best alternative comparison and additionality assessments. Include the effects of all affected resources—including energy, labor, and capital.

If the estimates are in actual (current) dollars, convert yearly current dollars to yearly constant dollars as of the stated year--as indicated by the Guide or Addendum to it--that EERE has selected for which $1.00=1.00. The Guide obtains the needed Gross Domestic

Product (GDP) Implicit Price Deflators from U.S. Department of Commerce's Bureau of Economic Analysis (BEA), at http://www.bea.gov/national/index.htm. These price deflators are routinely updated by BEA, and to prevent variations among the benefit-cost studies, caused merely by using different price deflator series, this Guide prescribes the series of price deflators to be used by all studies conducted within a funding cycle.

Show the calculated year-by-year economic benefits in tabular form for each separately treated technology or group of technologies within a cluster, as well as for each type of economic benefit. Show the sum of constant dollar cash flows as undiscounted economic benefits. An illustration is provided in Table II-6 from the geothermal benefit-cost study (Gallaher, et al, 2010). The table shows the estimation of productivity gains attributed to the DOE Geothermal Program due to its contributions to development of reservoir models.

Repeat the above tabular treatment for each separately treated technology or group of technologies within the cluster. For example, the referenced geothermal study provided separate analyses for four distinct technologies--one from drilling, one from reservoir development, one from well preparation, and one from plant technologies.

Provide an overall summation table that brings together the year-by-year constant dollar economic benefits for each technology or group of technologies within a cluster.

Show the overall undiscounted sum and also the overall PV results for economic effects, based on discount rates of 3% and 7%.

Table II-6. Example from the Geothermal Benefit-Cost Study (2010) of the Estimation of Productivity Benefits from Use of Reservoir Models

(1) Year	(2) Price per MWh of Electricity ($2008)	(3) Geothermal Electricity Generated (MWh)	(4) Electricity Generated by Geothermal After TOUGH Model for Reservoir Simulation Became Widely Used (MWh)	(5) Share of Geothermal Power Generated Due to Reservoir Modeling--based on 10% share (MWh)	(6) Economic Benefits from Reservoir Modeling (prior to attribution analysis) (thousands of $2008)	(7) Economic Benefits from Reservoir Modeling (prior to deduction of capital costs) Attributed to DOE (thousands of $2008)
1979	na	3,888,968	na	na	0	$0
1980	$106.8	5,073,079	1,184,111	118,411	$12,646	$2,909
1981	$114.2	5,686,163	1,797,195	179,720	$20,524	$4,721
1982	$119.4	4,842,865	953,897	95,390	$11,390	$2,620
1983	$118.6	6,075,101	2,186,133	218,613	$25,928	$5,963
1984	$113.4	7,740,504	3,851,536	385,154	$43,676	$10,046
1985	$113.5	9,325,230	5,436,262	543,626	$61,702	$14,191
1986	$111.0	10,307,954	6,418,986	641,899	$71,251	$16,388
1987	$106.7	10,775,461	6,886,493	688,649	$73,479	$16,900
1988	$102.8	10,300,079	6,411,111	641,111	$65,906	$15,158
1989	$100.7	14,593,443	10,704,475	1,070,448	$107,794	$24,793
1990	$98.7	15,434,271	11,545,303	1,154,530	$113,952	$26,209
1991	$97.9	15,966,444	12,077,476	1,207,748	$118,238	$27,195
1992	$96.7	16,137,962	12,248,994	1,224,899	$118,448	$27,243
1993	$96.1	16,788,565	12,899,597	1,289,960	$123,965	$28,512
1994	$93.9	15,535,453	11,646,485	1,164,649	$109,360	$25,153
1995	$91.7	13,378,258	9,489,290	948,929	$87,017	$20,014
1996	$89.6	14,328,684	10,439,716	1,043,972	$93,540	$21,514
1997	$87.9	14,726,102	10,837,134	1,083,713	$95,258	$21,909
1998	$85.5	14,773,918	10,884,950	1,088,495	$93,066	$21,405
1999	$83.0	14,827,013	10,938,045	1,093,805	$90,786	$20,881
2000	$83.3	14,093,158	10,204,190	1,020,419	$85,001	$19,550
2001	$87.2	13,740,501	9,851,533	985,153	$85,905	$19,758
2002	$84.8	14,491,310	10,602,342	1,060,234	$89,908	$20,679
2003	$85.8	14,424,231	10,535,263	1,053,526	$90,393	$20,790
2004	$85.3	14,810,975	10,922,007	1,092,201	$93,165	$21,428
2005	$88.3	14,691,745	10,802,777	1,080,278	$95,389	$21,939
2006	$93.5	14,568,029	10,679,061	1,067,906	$99,849	$22,965
2007	$93.3	14,637,213	10,748,245	1,074,825	$100,281	$23,065
2008	$98.2	14,859,238	10,970,270	1,097,027	$107,728	$24,777
Total NB, Undiscounted						$548,675

Notes: Cols 2 and 3 sourced from EIA by Gallaher, et al. (2010); Col 4= from Col 3, energy in each year after 1979, minus energy generated in 1979; Col 5=Col 4 energy amount x 10%; Col 6= price in Col 2 times the energy amounts in Col 5; and Col 7= DOE attribution rates for TOUGH (80%) and for other reservoir model development (20%). Increased capital costs due to use of the reservoir models offset some of the benefits. These are not included in Table II-6 for greater ease in exposition, but they are included in the benefit-cost study by Gallaher, et al. (2010).

►Treat qualitatively any economic effects of the selected technologies not captured by the quantitative economic assessment, as well as any economic effects realized from the remaining part of the cluster

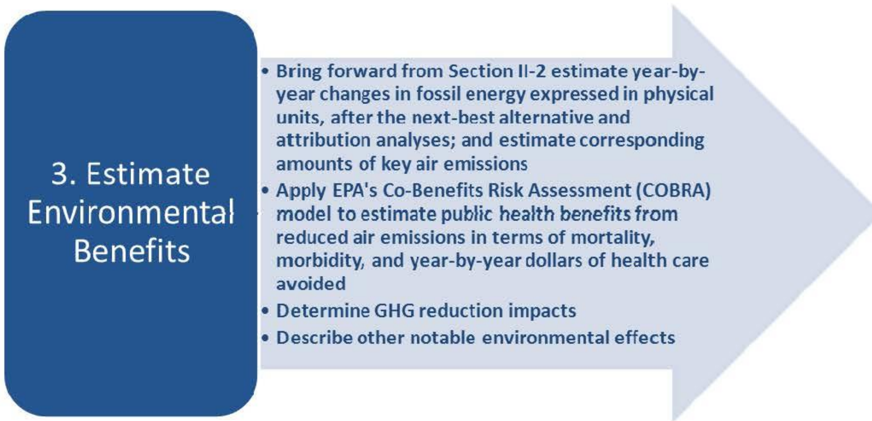
As noted previously, not all economic effects can be quantified. Some can be quantified but with great difficulty or with controversial results, while others can be quantified, but not necessarily in dollars. Economic effects not quantified in dollars are omitted from the economic return measures. Steps should be taken to include these effects as part of the overall findings, such that a judgment can be applied if there are conflicts between the results of the quantified economic performance measures and the non-quantified or non-monetized economic effects.

When there are known non-quantified or non-monetized effects omitted from the economic performance measures, OMB Circular A-4 recommends performing a "threshold" analysis to evaluate their significance. Threshold or "break-even" analysis addresses the question, "How small or how large could the value of the non-quantified or non-monetized effects be before it would offset the economic value from the quantified benefits?"

Providing explicit treatment of energy, environmental, security, and knowledge benefits within the EERE benefit-cost framework is expected substantially to reduce this problem of important effects being omitted from the analysis. Nevertheless, there may be important effects that are not captured in any of the four categories of benefits that should be considered.

Furthermore, the study approach is designed to capture only the benefits of selected technologies quantitatively. It is important, therefore, to provide a qualitative treatment of remaining elements—at minimum providing evidence that there is nothing in the cluster that will likely offset the dollar benefits of the selected technologies, or reduce confidence in the results.

3. *Estimate Environmental Benefits*



►Bring forward from Section II-2 estimated year-by-year changes in fossil energy expressed in physical units, after the next-best alternative and attribution analyses; and estimate corresponding amounts of air emissions.

The estimate of environmental benefits began in the previous section with the determination of changes in fossil-fuel consumption (i.e., coal, natural gas, and petroleum), reflective of the next-best alternative and attribution analyses. The year-by-year changes expressed in physical units by type of fuel are brought forward, and the corresponding amounts of air emissions are estimated for each fuel type.
Estimating emissions avoided may be assisted by the use of emission factors. An emissions factor is a representative value of the quantity of a given pollutant released to the atmosphere in association with using a designated fuel in a given activity. Emission factors are typically expressed as pounds per MWh of electricity produced for different generating sources, including natural gas, coal, oil, nuclear energy, municipal solid waste, hydropower, and a variety of renewable energy sources.

Examples of emission factors, provided by the U.S. Environmental Protection Agency (EPA) are in Table II-7. They are estimates of average emission rates from various fossil fuels used to generate electricity.

Table II-7. Emission Factors, Based on Average Emissions Rates from Fossil Fuels Used to Generate Electricity

Fossil Fuel Type	CO_2	SO_2	NO_x
Coal	2,249 lbs/1,000 kWh	13 lbs/1,000 kWh	6 lbs/1,000 kWh
Natural Gas	1,135 lbs/1,000 kWh	0.1 lbs/1,000 kWh	1.7 lbs/1,000 kWh
Petroleum	1,672 lbs/1,000 kWh	12 lbs/1,000 kWh	4 lbs/1,000 kWh

Source: EPA-issued emission factors for coal, natural gas, and oil, respectively, were found within the text at http://www.epa.gov/cleanenergy/energy-and-you/affect/coal.html; http://www.epa.gov/cleanrgy/energy-and-you/affect/natural-gas.html; and http://www.epa.gov/cleanenergy/energy-and-you/affect/oil.html.
Note the use of the following abbreviations: carbon dioxide (CO_2); sulfur dioxide (SO_2), nitrogen oxide (NO_X),, http://www.epa.gov/cleanenergy/energy-and-you/affect/oil.html

Software and tools for accessing information on EPA's air emission factors can be found at http://epa.gov/ttn/chief/software. EPA's eGRID comprehensive inventory of environmental attributes of electric power systems provides percentage use of multiple energy sources to generate electricity, aggregated data by state, by company, by electric grid district, and for the nation. CO_2 emission rates can also be found at http://www.epa.gov/cleanenergy/documents/egridzips/eGRID2010V1_1_year07_GHGOutputrates.pdf.

It is recognized that the science of assessing the impacts of various types of emissions and of multi-pollutant exposures is still under development, and new and improved models of assessment and prediction are emerging. Evaluators are encouraged to obtain and use the best available data and approaches for estimating changes in greenhouse gas (GHG) and air emissions.

►Apply EPA's Co-Benefits Risk Assessment (COBRA) Model to estimate public health benefits from reduced air emissions in terms of mortality, morbidity, and year-by-year dollars of health care avoided

EPA's Co-Benefits Risk Assessment (COBRA) model has been adopted by the EERE benefit-cost approach to provide first-order estimates of health effects and the economic value of health costs avoided resulting from changes in air emissions. The COBRA model has been used by EPA for regulatory analysis, such as for the Regulatory Impact Analysis of the Clean Air Interstate Rule (U.S. EPA, 2005).[19] Use of the COBRA model

[19] For a detailed discussion of studies used for health impact functions and unit values, see U.S. EPA (Environmental Protection Agency). (2005, March). *Regulatory impact analysis for the final Clean Air Interstate Rule*. EPA-452/R-05-002. Research Triangle Park, NC: Office of Air Quality Planning and Standards; Emission, Monitoring, and Analysis Division and Clean Air Markets Division. Available at http://www.epa.gov/cair/pdfs/finaltech08.pdf.

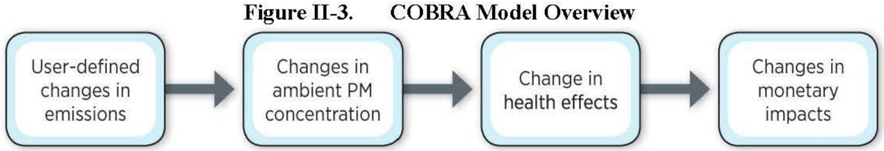
enables the health impact functions and the unit economic values used in our benefit-cost studies to be consistent with prior EPA analyses.

The COBRA Model is available on request from EPA, in the form of downloadable software and a user manual. (U.S. EPA *User's manual for the Co-Benefits Risk Assessment (COBRA) screening model*. Developed by Abt Associates Inc., June 2006.)

The model enables selection of air pollutants by type. The changes in pollutants by type are entered either as a percentage reduction (or increase) or as number of tons reduction (or increase). If the technology being evaluated is concentrated in several states, specific states can be selected within COBRA. If the technology's application is more widespread, the option of using "all states" can be selected. The model displays results in terms of change in the number of annual cases of respiratory deaths, illnesses by type, and associated costs.

At the core of the COBRA model is a source-receptor (S-R) matrix that translates changes in emissions to changes in particulate matter (PM) concentrations. The changes in ambient PM concentrations are then linked to changes in mortality risk and changes in health incidents that lead to health care costs and/or lost workdays. Figure II-3 provides an overview of the modeling steps.

Figure II-3. COBRA Model Overview



Source: EPA (2006)

In addition to entering changes in emissions, the user identifies the economic sector in which the emissions are reduced. The specified economic sector drives the underlying spatial distribution of emissions and the characteristics of the affected human population. The model then calculates the incidence of human health effects using a range of built-in health impact functions and estimated baseline incidence rates for each health endpoint. Table II-8 shows the different health endpoints that are provided by the model.

Table II-8. Health Endpoints Included in COBRA

Health Effect	Description/Units
Mortality	Number of deaths
Chronic bronchitis	Cases of chronic bronchitis
Nonfatal heart attacks	Number of nonfatal heart attacks
Respiratory hospital admissions	Number of cardiopulmonary-, asthma-, or pneumonia-related hospitalizations
Cardiovascular related hospital admissions	Number of cardiovascular-related hospitalizations
Acute bronchitis	Cases of acute bronchitis
Upper respiratory symptoms	Episodes of upper respiratory symptoms (runny or stuffy nose; wet cough; and burning, aching, or red eyes)
Lower respiratory symptoms	Episodes of lower respiratory symptoms: cough, chest pain, phlegm, or wheeze
Asthma emergency room visits	Number of asthma-related emergency room visits
Minor restricted activity days	Number of minor restricted activity days (days on which activity is reduced but not severely restricted; missing work or being confined to bed is too severe to be MRAD).
Work days lost	Number of work days lost due to illness

Source: COBRA User Manual

COBRA health effects are modeled individually based on epidemiological studies and functional forms, as described in the COBRA user's manual. For instance,

- **Mortality** risk estimates in COBRA are from an epidemiological study of the American Cancer Society cohort conducted by Pope et al. (2002). COBRA includes different mortality risk estimates for both adults and infants. Reductions in the risk of premature mortality are monetized using value of statistical life (VSL) estimates. Because of the high monetary value associated with prolonging life, mortality risk reduction is consistently the largest health endpoint valued in the study.

- **Chronic bronchitis** reflects results of a study by Abbey et al. (1995), that found statistically significant relationships between $PM_{2.5}$ and PM_{10} and chronic bronchitis.

- **Nonfatal heart attacks** are linked by Peters et al. (2001) to PM exposure.

- **Hospital admissions** include respiratory and cardiovascular, and are based on Sheppard et al. (1999) findings of asthma hospital admissions associated with PM, carbon monoxide (CO), and ozone, and findings of Moolgavkar (2000 and 2003) and Ito (2003) regarding a relationship between hospital admissions and PM.

- **Acute bronchitis** is modeled based on findings of a study by Dockery et al. (1996), that found episodes to be related to sulfates, particulate acidity, and, to a lesser extent, PM.

- **Upper respiratory symptoms** are modeled on finding of Pope et al. (2002) of a relationship between PM and the incidence of a range of minor symptoms.

- **Lower respiratory symptoms** are modeled on findings of Schwarz and Neas (2000) focused primarily on children's exposure to pollution from parental smoking and gas stoves.

- **Asthma related emergency room visits** are primarily associated with children under the age of 18, and modeled on findings of a study by Norris et al. (1999) that found significant associations between asthma ER visits and PM and CO.

- **Minor restricted activity days (MRAD)** in COBRA are based on research by Ostro and Rothschild (1989) using a national sample of the adult working population, aged 18 to 65, in metropolitan areas.

- **Work loss days** are modeled on findings of a study by Ostro (1987) which found that 2-week average PM levels were significantly linked to work loss days.

COBRA translates the health effects into changes in monetary impacts using per-unit monetary values described in the COBRA user's manual. Estimation of the monetary unit values vary by the type of health effect.

COBRA is expected to provide a conservative estimate of the health benefits of reducing air emissions for two reasons: (1) COBRA does not include the effects of many pollutants that may negatively affect health, and (2) COBRA does not fully capture the economic value of health effects of those pollutants that are included in the model. For instance, estimation of hospital admissions in dollars is based on cost of illness (COI) units that include the hospital costs and lost wages of the individual but do not capture the social (personal) value of pain and suffering.

Evaluators are to show in tables, first, the detailed mortality and morbidity data and associated costs avoidance for a selected year; and, second, the year-by-year heath care cost savings, and the undiscounted total. The first table is illustrated by the example in Table II-9 produced by application of the COBRA model in the ACE Benefit-Cost Study by Link (2010).

Table II-9. Illustration of Health Cost Calculations Results from the COBRA Model, Year 2000

(1) Category of Health Benefit	(2) Incidence	(3) Monetary Value of Health Impacts (millions $2008)
Mortality	531	$3,373.2
Infant Mortality	1	$9.1
Chronic Bronchitis	357	$158.2
Non-fatal Heart Attacks	836	$91.9
Respiratory Hospital Admissions	125	$1.7
Cardio-vascular Related Hospital Admissions	258	$7.2
Acute Bronchitis	883	$0.38
Upper Respiratory Symptoms	7,899	$0.24
Lower Respiratory Symptoms	10,473	$0.20
Asthma Emergency Room Visits	466	$0.17
Minor Restricted Activity Days	438,832	$26.8
Work Loss Days	74,012	$6.0
Total		$3,675.1

Source: COBRA model results from Link (2010).

The example continues in Table II-10, with year-by-year fuel savings, associated air pollutants, and monetary value of health impacts for the ACE Benefit-Cost Study (Link, 2010).

It should be noted that showing both estimates of changes in health incidents and associated health care costs entails double counting. However, these are kept separate in the study. The year-by-year health care cost savings are carried forward, together with economic benefits, to Step 6, and both are reflected in the bottom-line economic performance measures. The health incident data are used to explain what underlies the health care cost savings.

Using COBRA to estimate health benefits in dollar terms from reduced air pollution is deemed by experts in the field to provide sufficiently credible monetary estimates to warrant the approach of carrying the estimates forward and combining them with economic benefits to compute overall measures of economic performance (e.g., net present value benefits, benefit-to-cost ratios, and internal rate of return) in Step 6.

Table II-10. Health Benefits from Reduced Environmental Emissions from the ACE R&D Sub-Program's Research on Laser and Optical Diagnostics and Combustion Modeling (rounded), year-by-year

(1) Year	(2) Reduced Fuel Consumption with ACE R&D Sub-Program's Technologies (million gallons)	(3) PM (g/hp-hr) per EPA Regulations	(4) NO_x (g/hp-hr) per EPA Regulations	(5) SO_x (ppm) per EPA Regulations	(6) Monetary Value of Health Impacts (millions $2008)
1995	1,017	0.1	5.0	500	$2,597.8
1996	1,040	0.1	5.0	500	$2,681.1
1997	1,005	0.1	5.0	500	$2,615.8
1998	1,069	0.1	4.0	500	$2,435.4
1999	1,426	0.1	4.0	500	$3,278.1
2000	1,545	0.1	4.0	500	$3,675.1
2001	1,508	0.1	4.0	500	$3,623.5
2002	1,469	0.1	2.5	500	$2,735.7
2003	1,205	0.1	2.5	500	$2,263.4
2004	1,228	0.1	2.5	500	$2,327.9
2005	1,609	0.1	2.5	500	$3,078.0
2006	1,698	0.1	2.5	500	$3,279.0
2007	1,733	0.01	1.2	500	$1,114.0
Total	17,552				$35,704.8

Source: COBRA model; Link (2010).

►Determine GHG reduction impacts

The primary GHG to be accounted for in the benefit-cost analysis—and the only one required—is carbon dioxide (CO_2), provided in physical units. It is not monetized in current studies subject to this Guide.

The value of GHG is not expressed in monetary terms because the current value for social cost of carbon (SCC) is considered too uncertain. The range of confidence is too wide to provide useful quantification as an economic metric.

The current SCC value reported in the United States results from a 2009 effort by an interagency team of U. S. government specialists to estimate it. The result was a range of values from $5 to $65 per metric ton of carbon dioxide, with a "central value" of $21.[20]

When further improvements in the estimation of the SCC are made, and the range of estimate narrowed, GHG could be included in the benefit-cost studies as an additional metric valued in dollars, to be combined with the economic and health care cost savings and used to compute economic performance metrics. At this time, the advice of the review panel is to report GHG emissions in physical units and avoid increasing the degree of uncertainty of the economic performance measures.

►Describe other notable environmental effects

If there are other notable environmental effects other than air emissions—e.g., changes in water consumption, water discharges, land resource use, and solid waste generation—provide a qualitative treatment. If quantitative data are available, provide them together with a commentary description and explanation.

For indications of how the use of different energy generating sources may differentially affect the water and land environment, evaluators may wish to consult information compiled by the EPA. By generating source--such as natural gas, coal, oil, municipal solid waste, biomass, land-fill gas, nuclear energy, hydropower, wind, geothermal, and solar--effects on water, water discharges, land resource use, and solid waste generation are discussed.[21]

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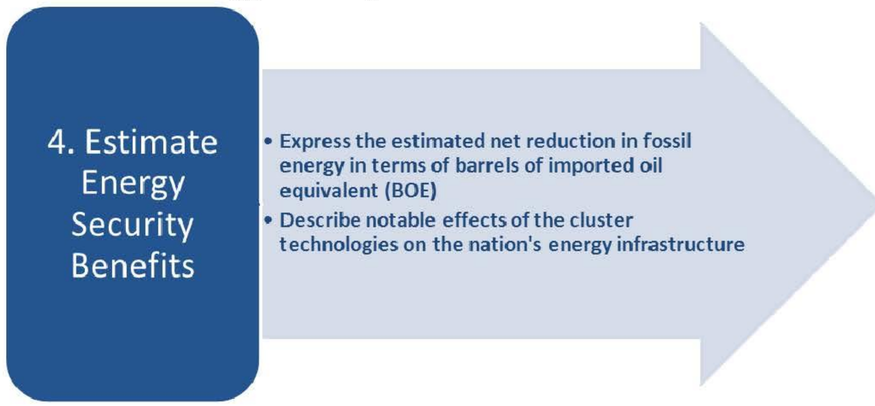
[20] An economic model, "integrated assessment model" (IAM), was used by the U.S. team to estimate the value of the SCC. The model incorporates knowledge from a number of fields of study, such as engineering, technology, behavior, and climate science, and uses mathematical formulas to simulate the relationships between economic activity and measures to control emissions and the desired environmental outcomes. Higher SCC numbers have been estimated by others, such as the UK's range of $41 – $124 per ton of CO2 with a central value of $83. The correct valuation remains controversial. For more information, see Interagency Working Group on Social Costs of Carbon (2010), and Bell and Callan (2011).

[21] As a starting point, one can find such information on-line at www.epa.gov/cleanenergy/energy-and-you/affect/index.html, under the heading "How does electricity affect the environment?"

4. Estimate Energy Security Benefits



Energy security benefits result from reducing disruptions in energy supply. They also result from reducing threats to the nation's energy infrastructure.

The energy security benefits included in the EERE approach take into account the following components:

- Quantitative estimates in physical units of reductions in barrels of oil equivalent (BOE) units of displaced imported fossil fuel as a proxy for a reduced dependence on imported energy supplies.

- Qualitative treatment of altered threats to the energy infrastructure.

►Express the estimated net reduction in fossil energy in terms of imported barrels of oil equivalent (BOE)

This estimation of reduction in BOE is driven by net reductions in fossil energy use in physical units, as calculated in Step 2. The estimation is accomplished in the following steps:

(1) Bring forward from Section 2 any estimated net reductions in fossil energy use expressed in physical units by type of energy. These fossil fuel estimates should be after the next-best alternative and attribution analyses.

(2) Translate reductions in fossil energy use into barrels of oil equivalent units, taking into account the energy source or mix of sources, and aggregating barrels across sources. Multiply by the percentage of U.S BOE demand that is imported, to reflect the share of BOE reduction associated with U.S. imported supply of oil.

Currently this share is approximately 50%.[22] Rather than apply year-by-year percentages, evaluators can use the share in the cut-off year for the benefit-cost study.

Barrels of oil equivalent is utilized as a recognizable unit of energy that serves as an indicator of national energy security benefits from reducing the quantity of imported oil. A barrel of oil equivalent (BOE) is based on the approximate energy released by burning a barrel of crude oil, where a barrel is defined as containing 42 gallons (approx. 159 liters) of crude. In terms of BTUs, one BOE is defined as 5.8 million BTU or 1,700 kilowatt hours or 1.7 MWh.

Table II-11 shows BOEs of common fossil fuels, including coal, natural gas, gasoline, and diesel fuel. It, or a similar conversion table, may be used to convert the quantity reductions in each type of fossil fuel to its BOE. Then, the imported share is taken as described above, and the results are summed for total BOE and displayed in the study report in tabular format.

Table II-11. Energy Conversion Table for Estimating BOE

British Thermal Units (Btu)	Cubic Feet Natural Gas (CF)	Short Tons Bituminous Coal (T)	Gallons of Gasoline (Gal)	Gallons of Diesel (Gal)	Barrels of Oil Equivalent (BOE)
5.8 Million	5,642	0.29	46.77	41.73	1.0

Source: Based on statements of BTU contents of common energy units provided by EIA.
Note: The heat content of crude oil varies among countries from about 5.6 MBtu per barrel to about 6.3 MBtu. Thus 5.8 MBtu is a nominal conversion factor widely used in the United States. Similarly the heat content of coal varies by type and region.

Energy security results should also be expressed in units, billions of gallons of gasoline equivalent (GGE) and millions of cubic feet of natural gas, for the appropriate fuel.

►Describe notable effects of the cluster technologies on the nation's energy infrastructure

In some cases, the program cluster evaluated may have implications for the security of the nation's energy infrastructure. For example, use of a distributed renewable energy source may reduce the vulnerability of central power plants to disruptions. If so, provide a qualitative description of the nature of these effects and provide supporting evidence.

The monetary valuation of energy security benefits from reductions of BOEs is not included in the assessment. It is recognized that associations among changes in energy

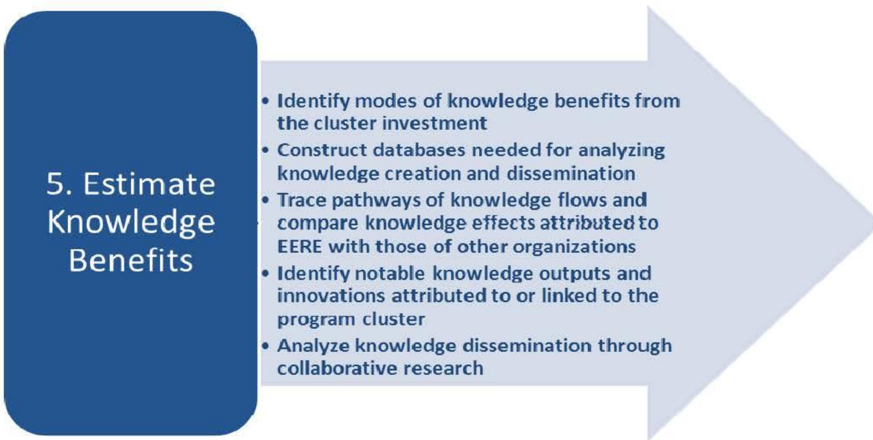
[22] According to EIA, 60% of U.S. crude oil was imported in 2005, and this share had dropped to 51% in 2009 and to 49% in 2010.

efficiency, energy supply, energy prices, and security impacts involve many assumptions, with causal relationships far more uncertain than for those entailed in estimating economic, environmental, and knowledge benefits.

Although attempts have been made by others to value in dollars the energy security benefits of achieving a given reduction in oil consumption, a satisfactory existing approach has not been identified for calculating the marginal change in the nation's energy security benefits as a result of specified percentage reduction in equivalent oil consumption.

Thus, attempts at monetary valuation of energy security benefits would be subject to far greater margins of error than for the retrospective monetary estimates of economic benefits and health care cost savings from avoided air emissions. The introduction of greater uncertainty in the monetary valuations would compromise the bottom-line benefit-cost results. For this reason, and based on recommendations of the Expert Panel which reviewed the Benefit-Cost Evaluation Methodology set forth in this Guide, the decision is to avoid monetary estimates of energy security benefits at this time—until an improved valuation approach is developed. Until then, reductions in physical units of imported BOEs, together with qualitative treatments of infrastructural effects will serve as an indicator of energy security benefits.

5. Estimate Knowledge Benefits



Two motivations drive the estimation of knowledge benefits in these benefit-cost studies:

(1) Additions to the nation's scientific and technical knowledge bases from R&D have a value far beyond the impacts that can be captured in monetary terms. To include knowledge benefits as an explicit component of R&D benefits is to recognize the larger and enduring impact of R&D on innovation and economic growth.

(2) One of the more challenging aspects of benefit-cost analysis of public R&D programs is adequately assessing attribution. By tracing from specific knowledge outputs of these evaluated programs to downstream innovations and commercial developments, the influence of the R&D is documented. This analysis, therefore, is expected to contribute to multiple lines of evidence in assessing attribution in Step 2.

►Identify modes of knowledge benefits from the cluster investment

Knowledge outputs of R&D programs are typically embodied in papers, patents, presentations, computer-based algorithms and other computational models and tools, prototypes and demonstration systems, test results, and standards; in humans—including students, professors, administrators, and researchers; and eventually in goods and services. Knowledge benefits may result from both explicit and tacit knowledge outputs. An R&D Program may contribute to the development of knowledge networks as EERE program researchers interact with and fund those in companies, universities, and other organizations in the United States and abroad.

As the Griliches/Mansfield's Model (See Part I, Section 2) shows, private returns and market spillovers in a targeted industry may result as knowledge drives innovation in competitive markets. Thus, the benefits of a Program's knowledge outputs are partially captured in a benefit-cost study's estimates of economic, environmental, and security benefits.

The realized and potential benefits of knowledge, however, are likely to extend well beyond those captured in a target market. As knowledge flows into, and yields benefits in other markets, the spillover gap—i.e., the excess of social returns over private returns—continues to expand.

The separation of knowledge benefits that have already been captured in the monetary valuation of other categories of benefits from those not yet captured is complex and is not attempted in this benefit-cost approach. Rather, identifying contributions of the cluster investment to the scientific and technical knowledge bases both within and outside the targeted industry area of application is an analysis goal. As noted above, the result is a more comprehensive and quantitative assessment of knowledge benefits than was provided by previous benefit-cost studies.[23]

The pathways from R&D knowledge outputs to commercial application of these outputs are typically long and complex. Use of a historical tracing framework employing interviews with program managers, researchers, and company managers; web searches; document and database review; bibliometric analysis; and other techniques is helpful in identifying and documenting these pathways. There may be multiple decades of DOE R&D in a given program cluster area. A variety of approaches will help to avoid missing critical connections. The objective is to assess the extent to which the knowledge was both created and used to influence downstream applications, and by whom.

To provide objectively derived, quantitative evidence of linkages that can be developed in a relatively non-intrusive manner, patent citation analyses has proven particularly useful. Patents have a central role in the innovation system, are consider closer to application than publications, and, as noted by Jaffe and Trajtenberg (2005), have been used extensively in the study of technological change. Patents are in the public domain and search engines can find them.

Publication analysis has also proven useful in assessing the knowledge benefits of program cluster investment. Analysis of coauthoring by program cluster researchers with those in other organizations may show linkages through collaborative research; patent-to-scientific paper citation analysis shows early influence of laboratory research on innovation; and publication-to-publication citation analysis shows pathways of knowledge flow through publications.

[23] Past benefit-cost studies have typically not separately treated knowledge benefits. An exception was the 2001 NRC benefit-cost study. However, a limitation of the 2001 NRC study was that it defined knowledge benefits as a "catch-all" for situations in which technology development had either failed, was still under development with no commercialization in sight, or had succeeded but was expected not to be adopted because economic and policy conditions were expected never to become favorable. Hence, the EERE approach to knowledge benefits represents a much more comprehensive treatment.

►Construct databases needed for analyzing knowledge creation and dissemination

To perform patent analysis, evaluators will need to construct databases of patents derived from the cluster investment. To do this, it is necessary to search Program files, the Office of Scientific and Technical Information (OSTI) database, and databases of patent offices, such as the U.S. Patent and Trademark Office (PTO), the European Patent Office (EPO), and the World Intellectual Property Organization (WIPO), using patent filters. It has been found that companies whose R&D has received public funding do not always acknowledged the public interest when filing resulting patents, and this omission may require searches of DOE annual reports, matching of identified patents with DOE-funded company research, and verification with DOE experts. When subprograms are assessed, special attention may be needed to identify the set of patents associated with a highly focused R&D effort.

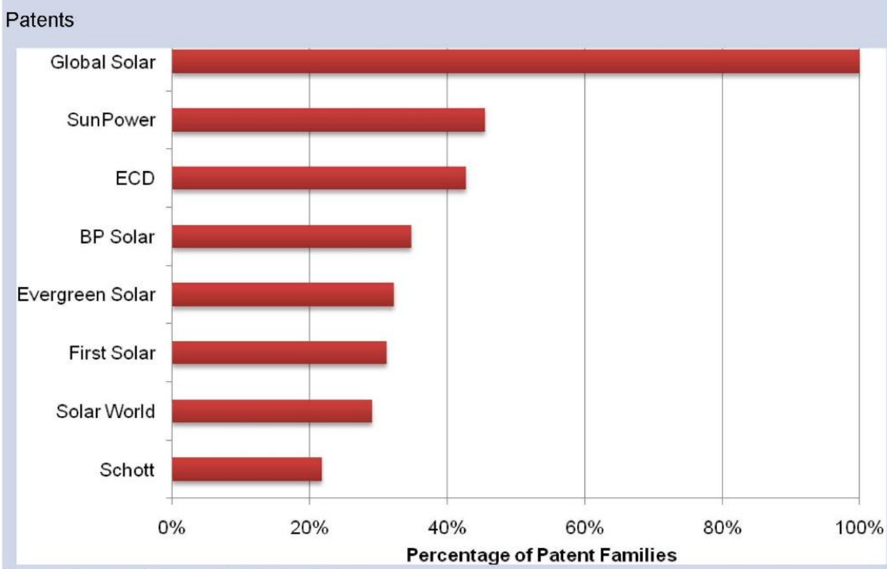
To avoid double counting of patents, evaluators will need to construct "patent families" which contain all patents based on an original patent. To perform comparisons of patenting intensity resulting from program cluster investment with that of other organizations, and to trace from commercial users back to earlier R&D sources, evaluators will need to identify relevant organizations who are innovators in the technology area of focus and their relevant patent portfolios. To provide country comparisons, relevant patent databases will need to be constructed by country of first issue. To identify highly significant patents, evaluators will need to construct and use citation indices to adjust for technology area and year of issue.

►Trace pathways of knowledge flows and compare knowledge effects attributed to EERE with those of other organizations

Two main approaches are used to trace patent linkages between program cluster R&D and downstream developments. One approach—forward patent tracing—takes a broad look at downstream linkages. Its purpose is to determine the influence of program cluster patents have had on the development of downstream technologies in all areas. The other approach—backward patent tracing—focuses specifically on linkages from downstream commercial developments in the targeted industry back to patents attributable to the program cluster R&D. These analyses are performed both at the organization level and at the individual patent level.

To test the strength of linkages of program cluster attributed patents to commercial applications, perform a backward citation analysis, starting with patents of the leading innovators in the field and see to what extent they link back to patents funded by the Program cluster, as compared with the extent of linkages to other organizations. This approach is illustrated by Figure II-4, which is drawn from the solar PV knowledge benefits study by Ruegg and Thomas (2011), performed in support of the solar PV benefit-cost study by O'Connor, et al. (2010).

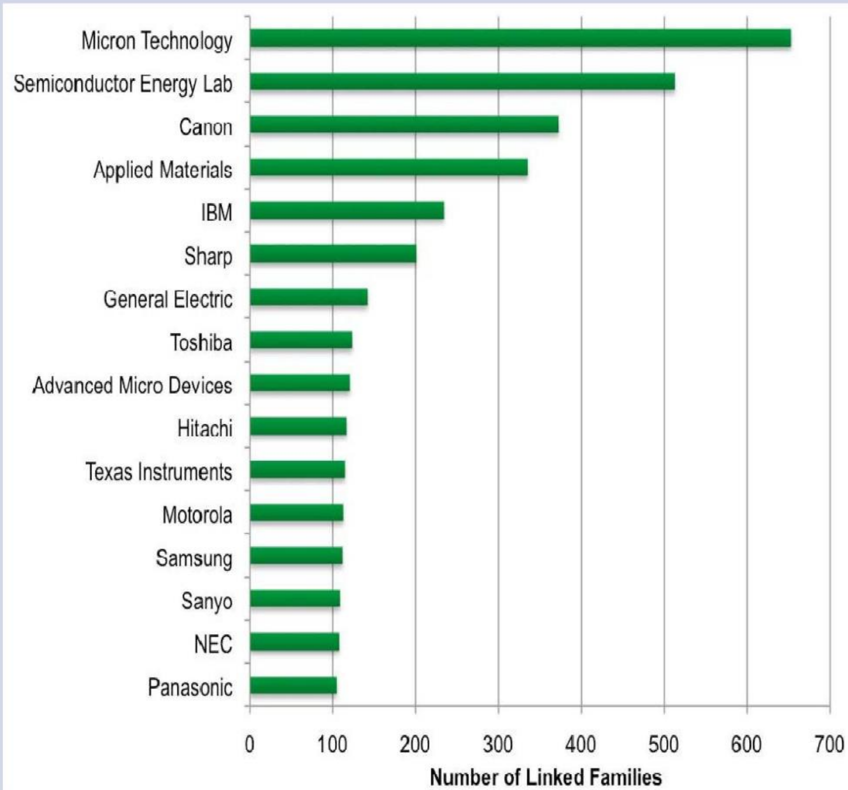
Figure II-4. Percentage of Solar Energy Patent Families of Top U.S. Solar PV Producers Linked to Earlier DOE-Attributed Solar PV



Source: Ruegg and Thomas, Solar PV (2011).

To determine linkages through patents attributed to the program cluster to not only the targeted industry but beyond to other industries, perform a forward citation analysis, starting with program-attributed patents and identifying subsequent patents that link back to these earlier program-attributed patents. An illustration of forward tracing at the organizational level is provided by Figure II-5, which is also drawn from the solar PV knowledge benefits study by Ruegg and Thomas (2011), in support of the solar PV benefit-cost study by O'Connor, et al. (2010). It highlights influence of the EERE's solar PV research beyond U.S. leading PV producers to leading companies in the semiconductor industry.

Figure II-5. Organizations from All Industry Areas with the Largest Number of Patent Families from All Technologies Linked to Earlier DOE-Attributed PV Patents



Source: Ruegg and Thomas, Solar PV (2011).

►Identify notable knowledge outputs and innovations attributed to or linked to the program cluster

A concept useful in tracing knowledge flows is that highly cited patents (i.e., patents cited by many later patents) tend to contain technological information of particular importance. A patent that forms the basis for many new innovations tends to be cited frequently by later patents.[24]

[24] This does not mean that every highly cited patent is important, or every infrequently cited patent is unimportant, but, research studies have shown a correlation between the rate of citations of a patent and its technological importance.

An example of notable (i.e., highly cited) PV innovations of companies linked back to EERE-attributed PV patents is given in Table II-12, drawn from the Ruegg and Thomas knowledge benefits study performed in support of the 2010 Solar PV Benefit-Cost Study by O'Connor, et al, 2010. The Citation Index adjusts for the type of technology and for the age of the patent, such that, for example, the Index value of 4.52 in the table's first row means that this patent (#4419533) has been cited approximately 4.5 times more often than would be expected of a patent of its age, within its technology area.

Table II-12. Highly Cited Solar Energy Patents of Top U.S. PV Producers Linked to Earlier DOE-Attributed PV Patents

Patent[a]	Issue Date	# Cites Received	Citation Index	Assignee	Title
4419533	1983	47	4.52	ECD	Photovoltaic device having incident radiation directing means for total internal reflection
5164019	1992	51	4.08	SunPower	Monolithic series-connected solar cells having improved cell isolation and method of making same
6534703	2003	12	3.12	SunPower	Multi-position photovoltaic assembly
6111189	2000	19	2.93	BP	Photovoltaic module framing system with integral electrical raceways
6353042	2002	12	2.92	Evergreen Solar	UV-light stabilization additive package for solar cell module and laminated glass applications
6570084	2003	11	2.86	SunPower	Pressure equalizing photovoltaic assembly and method
4514583	1985	31	2.82	ECD	Substrate for photovoltaic devices
4419530	1983	28	2.69	ECD	Solar cell and method for producing same
5746839	1998	30	2.64	SunPower	Lightweight, self-ballasting photovoltaic roofing assembly

Source: Ruegg and Thomas, Solar PV (2011).

Patent-to-publication citation analysis can be used to identify when a subsequent technological development has drawn more directly on a scientific base. Thus an extended feature of the patent analysis is to assess program-cluster papers and publications cited by patents as prior art. An example is provided by Table II-13, drawn from the knowledge benefits study by Ruegg and Thomas (2011).

Publication-to-publication citation analysis can also indicate notable technologies, and show pathways of knowledge dissemination.

Table II-13. EERE Geothermal Paper/Publications Linked to the largest Number of Patent Families through Two Generations of Citations

# Linked Patents	DOE Papers/Publications
203	"Interfaces and Mechanical Behaviors of Fiber-Reinforced Calcium Phosphate Cement Compositions," by T. Sugama, et al., prepared for the Geothermal Division U.S. Department of Energy; Department of Applied Science (June 1992)
197	"Microsphere-Filled Lightweight Calcium Phosphate Cements," by Sugama, T., et al., U.S. Department of Energy, Washington, D.C. under contract No. DE-AC02-76CH00016 (December 1992)
197	"Hot Alkali Carbonation of Sodium Metaphosphate Fly Ash/Calcium Aluminate Blend Hydrothermal Cements," by T. Sugama, *Cement and Concrete Research Journal*, vol. 26, No. 11, pp. 1661-1672 (1996)
192	"Calcium Phosphate Cements Prepared by Acid-Base Reaction," by Sugama, T. et al., *Journal of the American Ceramic Society*, vol. 75, No. 8, p. 2076-2087 (August 1992)
185	"Carbonation of Hydrothermally Treated Phosphate-Bonded Calcium Aluminate Cements," by T. Sugama, et al., U.S. Department of Energy, Washington, D.C. under contract No. DE-AC02-76CH00016 (Undated)
108	"Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Part 1--Development of a PDC Cutting Force Model," by Glowka, D.A., *JPT*, pp. 797-799, 844-849 (August 1989)
105	"Use of Single-Cutter Data in the Analysis of PDC Bit Designs: Part II--Development and Use of PDCWEAR Computer Code," by Glowka, D.A., *JPT*, pp. 850-859 (August 1989)
101	"Acoustical Properties of Drill Strings," by Drumheller, D., *The Journal of the Acoustical Society of America*, No. 3, New York, pp. 1048-1064 (March 1989)
56	"The Propagation of Sound Waves in Drill Strings," by Drumheller, D., et al., *The Journal of the Acoustical Society of America*, No. 4, pp. 2116-2125 (April 1995)
37	"Acoustical Properties of Drill Strings," by Drumheller D, Sandia National Laboratories, SAND88 0502 (August 1988)
32	*Sourcebook on the Production of Electricity from Geothermal Energy*, Kestin, J., editor, Publication No. DOE/RA/4051, Chap. 4, p. 536 (1980)

Source: Ruegg and Thomas, Geothermal (2011).

►Analyze knowledge dissemination through collaborative research

Linkages from the R&D of program clusters are also assessed and demonstrated through the analysis of publication coauthoring, and the identification of networks that have formed among individuals, organizations, associations, and other groups involved in an R&D effort and the use of R&D outputs.

6. Calculate Measures of Economic Performance and Summarize Other Effects

►Combine year-by-year dollar benefits from economic resources and health cost effects and compute economic performance measures, following conventions stated in the Guide.

Bring forward the year-by-year series of economic benefits (undiscounted) from Step 2 and the year-by-year series of health care benefits (undiscounted) from Step 3. Show the year-by-year series separately and also combined. Table II-14 gives an example from a recent benefit-cost study.

Calculate the economic performance measures for the two data series separately and combined, using the formulas given in Part I, Figure I-2.

Spreadsheet functions or similar computational tools can be used to calculate the economic performance measures, provided their use satisfies the set of conventions listed in Table II-15. (An EERE goal is that consistency be followed across the set of EERE benefit-cost studies.)

An example of the bottom-line economic performance measures is given in Table II-16 A and B, from the ACE R&D Benefit-Cost Study by Link (2010).

Table II-14. Economic Benefits of Reduced Fuel Consumption, Monetary Value of Health Impacts, and Total economic benefits from the 2010 ACE R&D benefit-cost study

Year	Dollar Value of Reduced Fuel Consumption (millions $2008)	Monetary Value of Health Impacts (millions $2008)	Total Economic Benefits (millions $2008)
1995	$1,502.0	$2,597.8	$4,099.8
1996	$1,683.7	$2,681.1	$4,364.8
1997	$1,547.3	$2,615.8	$4,163.1
1998	$1,410.7	$2,435.4	$3,846.1
1999	$1,996.8	$3,278.1	$5,274.9
2000	$2,817.2	$3,675.1	$6,492.3
2001	$2,526.5	$3,623.5	$6,150.0
2002	$2,283.6	$2,735.7	$5,019.3
2003	$2,097.7	$2,263.4	$4,361.1
2004	$2,491.7	$2,327.9	$4,819.6
2005	$4,189.2	$3,078.0	$7,267.2
2006	$4,834.5	$3,279.0	$8,113.5
2007	$5,115.4	$1,114.0	$6,229.4
Total	$34,496.4	$35,704.8	$70,201.1

Source: Link, 2010

Table II-15. Summary of Conventions for Computing Economic Performance Measures

- **Discount Rate**: 7% and a 3% real discount rates are to be used per OMB Circulars A-94 and A-4 pertaining to benefit-cost analysis, respectively, and the sensitivity of economic performance results will be displayed for 0% (undiscounted case), 3%, and 7% discount rates.

- **Base Year** (time to which all cash amounts are converted in a present value analysis): The base year to be used marks the onset of cash flow, which for the cluster economic performance measures is the year in which the investment in the technology cluster began.

- **Cash-Flow Modeling Conventions**: Cash flows are to be expressed annually and can be modeled as though they occur at the end of the year. A common practice in cash flow analysis is to model investment costs as occurring at the beginning of each year and benefits net of operating and maintenance costs as occurring at the end of each year. However, built-in formulations of popular spreadsheet program tend not to make this distinction automatically and require that the Evaluator to adjust the designated timing of investment cash flows, which is simple to do. Use of either cash-flow modeling convention is acceptable for these benefit-cost studies—that is, modeling all cash flows at the end of the year in which they occur, or, alternatively, modeling investment costs at the beginning of the year in which they occur and benefits net of operating and maintenance costs at the end of the year in which they occur. Alternatively a mid-year convention can be used. However, the study should indicate explicitly the cash-flow modeling convention is has used.

- **Constant Dollars**: All cash flows are to be converted to constant dollars as of the designated year for which $1.00 = 1.00 as found in the list of year-by-year GDP price deflator indices issued in the most recent Addendum to this Guide. (For the four EERE Benefit-Cost studies published in 2010, all current dollars were converted to constant 2008 dollars.)

- **Present Values**: All constant dollar cash flows are to be adjusted to equivalent present value amounts as of the base year (i.e., as of the year which marks the onset of cash flow).

- **Economic Performance Measures**: The three measures —NB, B/C, and IRR—in Figure I-2 and discussed in the section following are to be used to estimate the return on EERE's program investment in a defined technology cluster.

Table II-16A. ACE R&D Sub-Program and CRF Costs and Economic Benefits Associated with the ACE R&D Sub-Program's Research in Laser and Optical Diagnostics and Combustion Modeling

(1) Year	(2) Costs: ACE R&D Sub-Program (millions $2008)	(3) Costs: Combustion Research Facility (millions $2008)	(4) Total ACE R&D Costs (millions $2008)	(5) Total Economic Benefits (millions $2008)
1986	$27.402	$5.602	$33.004	–
1987	$29.005	$5.930	$34.935	–
1988	$27.785	$5.680	$33.465	–
1989	$26.525	$5.423	$31.948	–
1990	$25.929	$5.588	$31.517	–
1991	$22.869	$6.240	$29.109	–
1992	$23.611	$6.223	$29.834	–
1993	$20.550	$6.073	$26.623	–
1994	$17.587	$5.665	$23.252	–
1995	$13.890	$5.549	$19.439	$4,099.8
1996	$21.574	$6.154	$27.728	$4,364.8
1997	$24.714	$6.743	$31.457	$4,163.1
1998	$23.239	$6.547	$29.786	$3,846.1
1999	$46.230	$6.281	$52.511	$5,274.9
2000	$57.211	$5.796	$63.007	$6,492.3
2001	$62.475	$6.538	$69.013	$6,150.0
2002	$55.538	$6.332	$61.870	$5,019.3
2003	$63.714	$6.842	$70.556	$4,361.1
2004	$59.119	$6.605	$65.724	$4,819.6
2005	$52.593	$6.983	$59.576	$7,267.2
2006	$42.649	$6.567	$49.216	$8,113.5
2007	$49.379	$7.811	$57.190	$6,229.4
Total	$793.59	$137.17	$930.76	$70,201.1

Table II-16B. Example of Evaluation Performance Metrics Calculated from the Combined Economic and Health Care Benefits and the ACE R&D Subprogram Costs

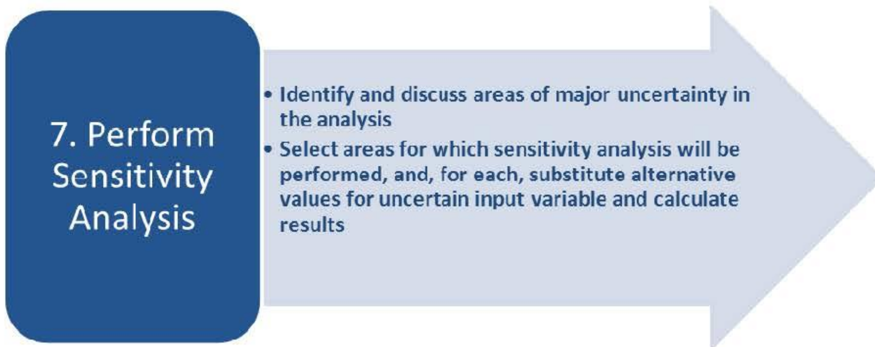
Metric	7% Discount Rate	3% Discount Rate	Internal Rate of Return
Present Value of Net Benefits (billions $2008)	$23.1	$42.6	
Benefit-to-Cost Ratio	53 to 1	66 to 1	
Internal Rate of Return			63%

Source: Link (2010).

►Characterize the extent to which the EERE cluster investment has been worthwhile from the standpoint of monetized benefits and costs and in terms of the other effects considered

The tests for using the various economic performance metrics to determine if an investment has been worthwhile are noted in Part I, section 2, ("Economic Performance Measures"). These simple tests are that the NPV is positive; that the BCR is greater than one; and that the IRR is greater than the required rate of return (as indicated by the OMB-specified discount rate). The extent to which an investment has been economically worthwhile is signaled by the size of these measures—the larger the measure, the more economically worthwhile the investment has been up to the evaluation cut-off year, others factors being equal. However, it is to be remembered that these economic metrics are based on partial benefits. Their implications for how worthwhile an investment has been are conservative and need to be conditioned by the other impacts which were not included in the metrics.

7. Perform Sensitivity Analysis



Previously acknowledged is that multiple discount rates are required by the Guide to calculate the economic performance measures: discount rates of 0%, 3%, and 7% (See Part 2, Step 2). In effect, use of the multiple rates will show sensitivity of the results to the discounts rate.

Some other input variables may have been expressed using multiple values, such as a range of possible values. Other input variables may have higher degree of uncertainty surrounding them. Uncertainties in the evaluation need to be explicitly acknowledged and treated.

►Identify and discuss areas of major uncertainty in the analyses, such as the following:

- When a range of implied or explicit values were obtained for an input variable;
- When an alternative estimation approach could have been justified for use, and its use is expected to have produced different results than the approach taken; and
- When a given input variable or assumption is expected to have a large effect on outcome, and there is uncertainty about it.

►Select areas for which sensitivity analysis will be performed, and, for each, substitute alternative values for uncertain input variable and calculate results

- To test sensitivity of results to a range of input values, use the low and high ends of the range to generate a range of outcomes. (See Example A below, Table II-17)

- To test the sensitivity of results to a different estimation approach for a key input variable, go back to the stage of the analysis in which the key input first appears and recalculate it using the alternative approach; then feed the results through all subsequent affected calculations. (See Example B below, including Tables II-18 and II-19)

Sensitivity Analysis--Example A: Table II-17. Sensitivity to Variation in Acceleration Effect and Discount Rate

Measure	12-year Acceleration Effect	10-year Acceleration Effect	15-year Acceleration Effect
Net benefits (billion 2008$)	$15.03	$10.68	$22.17
Internal rate of return	17%	14%	20%
NPV @ 7% (billion 2008$; base year = 1975)	$1.46	$0.86	$2.39
Benefit-to-cost ratio @ 7%	1.83	1.49	2.37
NPV @ 3% (billion 2008$; base year = 1975)	$5.72	$3.99	$8.53
Benefit-to-cost ratio @ 3%	3.24	2.56	4.35

Source: O'Connor, et al. (2010)

Sensitivity Analysis--Example B: Test the Sensitivity of Results to a Different Estimation Approach

The test is for sensitivity to the way the energy savings were calculated. Initially they were calculated based on a statistical relationship found between brake thermal efficiency (BTE), a measure of fuel efficiency, and resulting miles per gallon (MPG), based on the period 1970-2007, and this relationship was assumed to apply to the period 1995-2007. In the initial analysis, this statistical relationship resulted in 17.6 billion gallons of diesel fuel oil saved from 1995 through 2007, with an IRR of 63%.

The alternative approach assumed that new heavy-duty diesel trucks would each year consume a proportionate amount of fuel each year and that proportion would remain constant over time. The sensitivity analysis showed that using the alternative method of calculating energy savings resulted in 15.1 billion gallons of diesel fuel oil saved, and an IRR of 50%. Results on energy savings and on the bottom-line economic performance measures from using the alternative approach to estimating energy savings are shown in Tables II-18 and II-19.

Table II-18. Sensitivity Testing of Reduced Fuel Consumption from the ACE Subprogram R&D Using an Alternative Method (Link, 2010)

Year	Reduced Fuel Consumption with ACE R&D Sub-Program's Technologies (million gallons)	Average Retail Price Diesel Fuel (per gallon)	Dollar Value of Reduced Fuel Consumption (millions $)	GDP Implicit Price Deflator (2008=100)	Dollar Value of Reduced Fuel Consumption (millions $2008)	Dollar Value of Health Impacts (millions $2008)
1995	169.2	$1.11	$187.85	75.160	$249.94	$432.2
1996	318.5	$1.24	$394.89	76.591	$515.59	$821.1
1997	475.1	$1.20	$570.06	77.943	$731.38	$1,236.6
1998	651.0	$1.04	$677.03	78.824	$858.91	$1,483.1
1999	874.4	$1.12	$979.28	79.983	$1,224.37	$2,010.1
2000	1,067.6	$1.49	$1,590.67	81.715	$1,946.61	$2,539.5
2001	1,197.0	$1.40	$1,675.86	83.561	$2,005.55	$2,876.2
2002	1,314.9	$1.32	$1,735.61	84.915	$2,043.94	$2,448.7
2003	1,437.8	$1.51	$2,171.05	86.742	$2,502.88	$2,700.7
2004	1,595.4	$1.81	$2,887.74	89.203	$3,237.27	$3,024.4
2005	1,809.2	$2.40	$4,342.18	92.180	$4,710.54	$3,461.0
2006	2,038.1	$2.71	$5,523.29	95.183	$5,802.81	$3,935.8
2007	2,171.8	$2.89	$6,276.54	97.908	$6,410.65	$1,396.1
Total	15,119.9				$32,240.44	$28,365.5

Example B, continued.

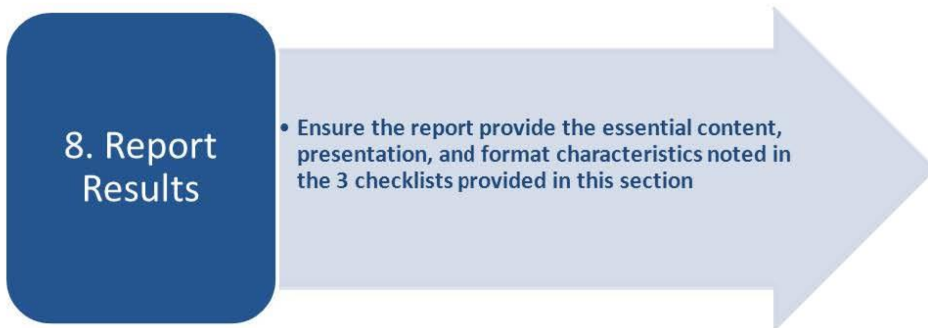
Table II-19 Evaluation Metrics for ACE Subprogram Re-Calculated to Show Sensitivity to the Alternative Assumption for Calculating Energy Savings in Table II-18

Metric	7% Discount Rate	3% Discount Rate	Internal Rate of Return
Present Value of Net Benefits (billions $2008)	$17.8	$35.0	
Benefit-to-Cost Ratio	41 to 1	54 to 1	
Internal Rate of Return			50%

Source: From Link (2010)

Note that the sensitivity testing in Example B does not say which estimation approach is better for estimating diesel fuel cost savings; it does show the results based on either calculation approach are quite strong.

8. Report Results



Goals to be achieved by Step 8 are that evaluators:

- Produce benefit-cost reports, and supporting study outputs, that will serve as effective communication tools with diverse program stakeholders about the study, its findings, and its implications.
- Maintain best practices and a level of consistency with other benefit-cost studies/reports that have similar purpose—while reflecting the unique requirements and data availability issues that evaluators typically encounter across studies.
- Produce reports whose input data, assumptions, and calculations are sufficiently transparent that they can be replicated and verified by others.
- Present data that can be added to a meta data infrastructure for EERE's benefit-cost studies which will allow for multiple, discrete packages of study data that are linked to allow aggregate calculations and that inform program data collection plans and activities.

► Ensure the study report provides essential content characteristics by following the “Contents Checklist” found in Table II-20

Table II-20. Contents Checklist

Use this column to rate each content element as: _Found _Not Found _Adequate _Inadequate	Content Topics	Essential Characteristics
	Statement of Study Design, Objectives, Approach, Nature of Findings; and Impacts Included and Excluded	• Benefit-cost framework • Cluster approach • Statement of evaluation objectives • Retrospective analysis with cut-off year and no life-cycle benefits counted • Conceptual models based in theory used • Focus on public returns only • All findings are evidence-based • Conservative, lower-bound estimates of findings, with reasons why • Clear delineation of all categories of impacts included--those with monetary valuation, those with other quantitative valuation, and those with qualitative valuation • Identification of effects excluded from the evaluation
	Description of Program Cluster Overall and Selected Technologies for Detailed Treatment	• How and why program cluster was selected • Overall description of cluster • Description of selected technologies for detailed treatment, and rationale for selection • Method of treatment for each technology (or group) separately assessed • Discussion of other elements in the cluster (not included for detailed treatment) and their likely impact on economic returns • Cost: year-by-year total cluster costs and year-by-year costs of the selected technologies

	Next-best Alternative	• Designation for each selected technology (or group) individually assessed • Description of resulting baseline used in estimating differential effects of each technology (or group) • Explicit treatment of next-best alternative, separate from attribution assessment
	Attribution Assessment	• Assessment of context in which the program operated and external influences that may constitute rival explanations of outcomes • Fully documented attribution matrix for each technology (or group) individually treated • Timeline of relevant developments • Treatment of rival explanations of outcome • Clear representation of attribution level, such as by % share of differential effect for each technology (or group) attributable to the public program cluster • Explicit treatment of attribution, separate from next-best alternative assessment
	Data Quality, Collection Tools, Uncertainties, and Exposition	• Use of valid protocols and procedures in data collection • Statement of critical assumptions • Inclusion of all data used in the analysis • Identification of data sources • Identification of uncertainties, and data distributions where relevant • Inclusion of interview and survey tools • List of interviewees
	Estimation of Each of 4 Category of Benefits--(1) Energy & Other Economic Benefits, (2) Environmental Benefits, (3) Energy Security Benefits, and (4) Knowledge	• Systematic and transparent analyses, with all steps documented, and approach/results replicable • Credible treatment of (and explanation thereof) of both demand and supply sides of the analysis, with fully documented assumptions

		• Separate treatment of: Energy Effects, including types of energy and physical quantities
	Calculation of Economic Performance Measures	• Measures include NB (undiscounted), NPV based on 3% and 7% discount rates, BCR based on 3% and 7% discount rates, and IRR • These measures are separately calculated for: (1) Energy & Other Economic benefits (2) Combined Economic and Health Cost Avoidance
	Sensitivity Analysis	• Performed to highlight effects of uncertain or controversial variables, assumptions, and estimation methods
	Overall Conclusions	• Summary of evidence-based findings • Implications of findings • Indication that all stated evaluation objectives have been achieved • Identification of study limitations

►Ensure the study report provides essential format characteristics by following the "Format Checklist" found in Table II-21

Table II-21. Format Checklist

Use this column to rate each report component as: _Found _Not Found _Adequate _Inadequate	**Report Components**	**Description**
	Title Page	• Title • Date • Prepared by... • DOE cover design

	Preface (if desired by DOE)	DOE prepared, e.g., description of mission, objectives, programs, rationale for public investment, and purposes of retrospective impact evaluation
	Acknowledgements	Contributors and reviewers
	Notice	DOE prepared
	Executive Summary	• Written for audience of diversion backgrounds, designed to communicate quickly and concisely the most important findings, conclusions, and implications • Specific inclusion of overall results summation table including the metrics included in Table I-1 of this Guide
	Table of Contents and lists of Tables and Figures	• 3-levels of headings for TOC • Electronically keyed to report sections to facilitate easy movement of the reader through the report.
	Main Body of the Report	• All elements of essential contents as outlined in Table II-20 • Separate Sections on each of the 4 categories of benefit : o Energy & Other Economic Benefits o Environmental Benefits (including GHG & Health Care Cost Savings) o Energy Security Benefits o Knowledge Benefits
	References	listing of references cited in the report; not a general reading list
	Appendices/Attachments	Supporting information that can be moved out of the main body of the report for improved readability, but that is strongly germane to the presentation and likely desired by certain readers
	Index, List of Terms, List of Abbreviations	Discretionary

►Ensure the study report provides essential presentation characteristics according to the "Presentation Checklist" found in Table II-22

Table II-22. Presentation Checklist

Use this column to rate the report's presentation according to each essential characteristic as: **_Adequate** **_Inadequate**	**Essential Presentation Characteristics**
	Concise, clear, transparent exposition
	Rigor demonstrated in data collection, analyses, and interpretation
	Document is accurate and reliable; free of errors of fact or logic
	Findings are objectively derived, testable, and reproducible
	Study has internal and external validity
	Study has credibility among stakeholders

►Use these Content, Format, and Presentation Checklists throughout the study

The checklists are intended for use by evaluators and by project managers on an on-going basis to keep the report development on track. They may also be used by report reviewers.

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Attachment 1

Drivers for Public Accountability

A number of directives and guidance memorandum from the Executive and Congress branches set impact evaluation expectations for EERE programs.

Executive Orders and OMB Memorandum:

- OMB Memorandum for the Heads of Executive Departments and Agencies, July 29, 2010 (Memo M-10-32) and Oct. 7, 2009 (Memo M-10-01) -- **increased emphasis on program evaluation in Federal Agencies.** http://www.whitehouse.gov/sites/default/files/omb/assets/memoranda_2010/m10-01.pdf

- OMB Budget Action Request (Memo 10-49), July 29, 2010 – **mandatory agency program evaluation inventory.** http://www.whitehouse.gov/omb/memoranda_default

- OMB and White House Office of S&T Policy Memorandum for the Heads of Executive Departments and Agencies on Science and Technology Priorities for the FY 2011 Budget, August 2009; **calls for R&D agencies to conduct evaluations and strengthen capacity.** http://www.whitehouse.gov/briefing-room/presidential-actions/presidential-memoranda

- OMB Performance Rating Assessment Tool (PART), 2003-2008; **set expectations for periodic systematic evaluations to be used to demonstrate results.** http://www.whitehouse.gov/omb/memoranda_m03-06/

- ARRA **unprecedented requirements for transparency & accountability**, 2009. http://www.recovery.gov/About/Documents/InitialRecoveryActImplementingGuidance_Feb18.pdf

- Executive Order 13450: Improving Government Program Performance, November 2007; **agencies shall spend taxpayers' dollars efficiently & effectively.** http://www.whitehouse.gov/sites/default/files/omb/assets/performance_pdfs/eo13450.pdf

Congress:

- GPRA Modernization Act of 2010 – **each agency shall make available on its public website an update on its performance. Agency strategic plans must include "... a description of the program evaluations used in establishing or revising general goals and objectives," and Agency performance reporting has to " include the summary**

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findings of those program evaluations completed during the period covered by the update." http://www.gpo.gov/fdsys/pkg/BILLS-111hr2142enr/pdf/BILLS-111hr2142enr.pdf

- House Committee Reports HEWD, 2008/2009/2010, **calls for reporting on return on investment.** http://www.google.com/url?sa=t&source=web&cd=7&ved=0CEgQFjAG&url=http%3A%2F%2Fscience.energy.gov%2F~%2Fmedia%2Fbudget%2Fpdf%2Fsc-congressional-appropriations%2FFy-2012%2FHouse-bill%2FHEWD-FY12-Committee-Report---Final_SC_Only.pdf&rct=j&q=house%20committee%20reports%20hewd&ei=tLJnTr3VIcj50gGHipDKCw&usg=AFQjCNHDI8M3zhyIR3C7rQZrcdAbjDDd5A&cad=rja

- Department of Energy Organization Act of 1977 (42 USC 5815(b)) – **grants administrative authority for agencies to conduct program evaluations.** http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=browse_usc&docid=Cite:+42USC5815

Attachment 2

Guiding Principles for Evaluators

The following is a summary of highlights of the American Evaluation Association (AEA) guiding principles that bear on expected conduct of evaluators in performing the EERE benefit-cost studies:

1. Systematic Inquiry: Evaluators conduct systematic, data-based inquiries.

   This principle requires that evaluators adhere to the highest technical standards appropriate to the methods they use; that they explore with the client the strengths and weaknesses of various evaluation questions and approaches; and that they communicate their methods and approaches accurately and in sufficient detail to allow others to understand, interpret and critique the results.

2. Competence: Evaluators provide competent performance to stakeholders

   This principle requires that the evaluation team has the education, abilities, skills, and experience to carry out the proposed evaluation tasks.

3. Integrity/Honesty: Evaluators display honesty and integrity in their own behavior, and attempt to ensure the honesty and integrity of the entire evaluation process.

   This principle requires evaluators to avoid conflict of interest and the appearance of a conflict; that evaluators not misrepresent their procedures, data, or findings; and that they should attempt to prevent or correct misuse of their work by others.

4. Respect for People: Evaluators respect the security, dignity and self-worth of respondents, program participants, clients, and other evaluation stakeholders.

   This principle requires that evaluators seek a comprehensive understanding of the important contextual elements of the evaluation; that they obtain informed consent from those participating and inform participants of limits of confidentiality; and that evaluators should conduct the evaluation and communicate its results in a way that avoids unnecessarily negatively affecting the interests of stakeholders while not compromising the integrity of the evaluation findings.

5. Responsibilities for General and Public Welfare: Evaluators articulate and take into account the diversity of general and public interests and values that may be related to the evaluation.

This principle requires that evaluators should consider not only the immediate outcomes but also broader assumptions, implications and potential side effects; that they should present results clearly and simply so that clients and other stakeholders can easily understand the evaluation process and results; and evaluators have obligations that encompass the public interest.

In summary, Principal Investigators are asked to support their benefit-cost analysis by collecting as many lines of evidence from independent sources as possible within practical constraints of data availability, time, and resources, and to use transparency in discussions of data collection, calculations, and analysis.

Attachment 3

Comparison of the EERE Approach with the 2001 NRC Approach

Summary:

For those who wish to know how the EERE approach modified an earlier NRC approach, a brief overview is provided here.

Figure A3-1 summarizes a comparison of features of the EERE and 2001 NRC approaches.. The upper left shows the original 2001 NRC framework, and the lower right shows the EERE modified framework as the yellow highlighted portion of the table, emphasizing EERE's greater focus on retrospective benefits and costs than the NRC approach.

Figure A3-1. Modified NRC Framework[25] Only Retrospective Benefits are Included

Original NRC Framework

	Realized	Options Value	Knowledge
Economic			
Environmental			
Security			

Source: Energy Research at DOE: Was It Worth It?, NRC, 2001

Modified Framework

Degree of uncertainty →

Ultimate outcomes ↕

	Realized (Retrospective)	Expected (Prospective)	Option Value
Economic[1]			
Environmental			
Security			
Knowledge			

1/ Includes energy benefits in the calculation

Source: EERE Benefits Analysis Workshop, 2004

Table A3-1 summarizes the comparison of 2001 NRC Approach to EREE modifications. In the first column are main features of the approach of the 2001 NRC Study; in the

[25] Source: Benefits Workshop, 2002

second are main features of the EERE approach. Features are aligned to allow the reader to see the modifications.

Table A3-1: Comparison of 2001 NRC Approach to EERE Modifications

NRC Study, 2001	EERE Modifications
SCOPE	
• Selected technology mix, winners & losers	• Detailed benefit-cost analysis of several technologies where economic and other benefits from a program cluster is compared against the entire program or cluster investment cost
• Technologies selected from the early 1970's to 2000 period	• Technologies selected from the early 1970's to 2008 period
BENEFITS INCLUDED	
• Benefits resulting from all capital stock installed through the present plus 5 years (in that case 2005) calculated over the entire future life-cycle of all these installations	• Economic benefits resulting from all capital stock installed up to the cutoff year. Future life-cycle benefits are excluded.
• It is to be determined if the NRC study included projected impacts for technologies not yet commercialized	• 'Realized' outcomes counted only for technologies that are already in the market, as indicated above
• Knowledge treated as qualitative catch-all for situations of technology failure in development or/and in deployment, plus descriptive listing of what were considered major technical accomplishments	• Assessment of knowledge creation and dissemination will not be limited to cases of failure. Rather identifying knowledge creation and dissemination will encompass both successful and unsuccessful technologies, within and outside the target industries. Historical tracing will identify paths and extent of knowledge flow, as well as recipients of the knowledge
• Environmental benefits - NOx, SO_2, and Carbon. Proxy values for the mitigation/ damage costs	• Avoided NOx, SO_2, PM, CO_2 equivalents. Avoided adverse health incidences associated with air emissions. Health care costs valued in dollars using EPA CPBRA model. Dollar value of CO_2 is excluded.

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NRC Study, 2001	EERE Modifications
• Security benefits – Oil and LPG (Q); Electricity reliability (Y/N); Valued using $3-20/barrel based on the probability and potential impact of oil disruptions; no valuation of infrastructure threat avoidance beyond yes/no/don't know.	• Security benefits for oil and natural gas in physical units and BOE equivalent. Qualitative treatment of energy benefits.
• Work productivity, exports addressed qualitatively	• Value of increase in work productivity and exports addressed qualitatively
• Macroeconomic effects (e.g., job creation) not considered; Regional shifts not considered; Rebound effect not considered	• Job impacts excluded. Regional shifts not considered; Rebound effect not considered
• Options value addressed qualitatively	• Options value not applicable because only commercialized technologies are selected
RULES ABOUT CALCULATIONS, ATTRIBUTION	
• Next best technology is conventional technology	• Next best technology could be conventional, best available, or earlier generation of subject technology - determined on case by case basis
• 5 year rule-of-thumb to apportion credit for impact to Govt. vs. private R&D. 5 year rule assumes anything the public sector does would have been done by the private sector anyway without the Govt. within 5 years.	• Additionality analyzed on a case-by-case basis; not using a rule of thumb
It is to be clarified whether benefits/costs for lifetime of installations were cut off at 2005, or whether as stated on p. 88 of the 2001 report, benefits were calculated for the entire lifetime of installations—including lifetimes of all the installations up to 2000 and also all the installation up to 2005—i.e., a 5 year cut-off appears to have applied to the installations included—but not to the assumed	• Prospective benefits are excluded

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NRC Study, 2001	EERE Modifications
lifetimes of those installations. However, there is disagreement about the approach that needs to be clarified.	
• No distinction in attribution of Govt. R&D vs. other factors driving market success of innovation	• Addresses various aspects of attribution (Govt. R&D vs. private sector; other market drivers—e.g., Production Tax Credits, etc.); ; use of an attribution matrix framework
• Partitioning attribution—NRC study not able to apply a satisfactory approach	• Use of the concept of "additionality", which describes what the gov't. R&D added that would not have occurred otherwise. Other qualitative, logical arguments will be provided in support of additionality findings.
• Levels of influence of R&D vs. standards/deployment activities not attempted	• Qualitative discussion will address the levels of influence of the R&D vs. standards/deployment activities
• No consideration of international effects	• Flows of technologies between countries and benefits of this will be recognized, as well as benefits of developing technologies within U.S.
• No discounting	• Discounting, using the current OMB guidance for public benefit-cost analysis
• Deflators -- all values in constant 1999 dollars, adjusted using GDP deflators	• All values will be appropriately adjusted to constant dollars as of the end of study's cutoff year, taking into account the discounting approach used. (Because the discount rate is a real rate, GDP price deflators are applied prior to discounting.)

Exploring Cost-Benefit Analysis of Research, Development and Innovation Infrastructures: An Evaluation Framework

EXPLORING COST-BENEFIT ANALYSIS OF RESEARCH, DEVELOPMENT AND INNOVATION INFRASTRUCTURES: AN EVALUATION FRAMEWORK

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Abstract

Governments, funding agencies and policy makers have high expectations on research, development and innovation (RDI) infrastructures in the context of science and innovation policies aimed at sustaining economic growth in the long term. The stakes associated with their selection and evaluation are therefore high.

Cost-benefit analysis of RDI infrastructures is a new field. The intangible nature of some benefits and the uncertainty associated to the achievement of research results have often discouraged the use of a proper CBA for RDI infrastructures. Recently, some attempts to develop a CBA theoretical framework for RDI infrastructures have been made in the context of the use of Structural Funds by the Czech government and JASPERS. Moreover, the new Guide for the CBA of investment projects in the context of Cohesion Policy, recently adopted by the European Commission (2014) provides guidelines to appraise RDI projects, but also admits that – due to lack of experience and best practices – further steps are needed to improve the evaluation framework.

This paper presents the results and the lessons learned on how to apply ex-ante CBA for major RDI infrastructures by a team of economists and scientists at the University of Milan and CSIL during a three-year research project supported by a EIBURS grant of the European Investment Bank Institute. Albeit the comprehensive conceptual framework presented in the paper builds on principles firmly rooted in CBA tradition, their application to the RDI sector is still in its infancy. So far, the model has been applied on two cases in physics involving particle accelerators (the Large Hadron Collider (LHC) at CERN and the National Centre for Oncological Treatment (CNAO) in Italy)).

In a nutshell, the model presented break down benefits into two broad classes: i) use benefits, held by different categories of infrastructure's users such as scientists, firms, students and general public visitors, and ii) non-use benefits, denoting the social value for the discovery potential of the RDI infrastructure regardless of its actual or future use. We argue that the social value of discovery can be estimated with contingent valuation techniques. Another significant feature of our approach is the stochastic nature of the CBA model, intended to deal with the uncertainty and risk of optimism bias in the estimates.

Key words: Research infrastructures, Cost-benefit analysis, Public good, Knowledge

JEL codes: D61, D81, I23, O32

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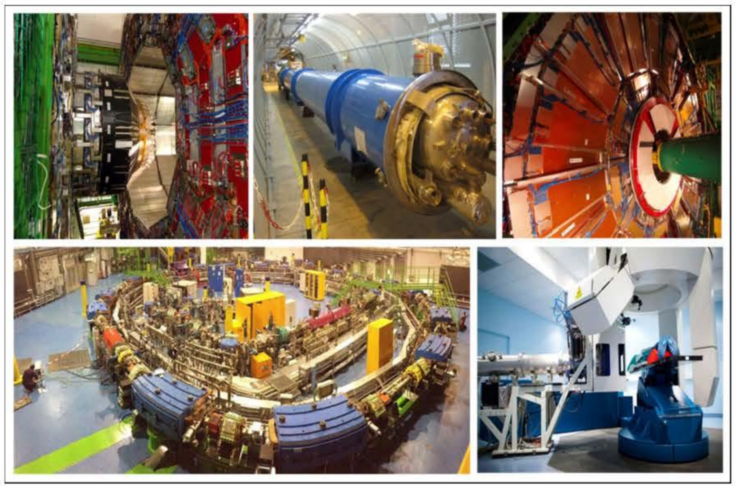

1

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Photo credits: 1) The Large Hadron Collider, CMS detector. Source: Authors. 2) The Large Hadron Collider. Source: Authors. 3) The Large Hadron Collider, CMS detector. Source: Authors. 4) The CNAO synchrotron. Source: Authors. 5) The CNAO treatment room, Source: CNAO Foundation.

European Investment Bank • Institute

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Abbreviations

CBA	Cost-benefit analysis
CERN	European Organization for Nuclear Research
CNAO	National Hadrontherapy Centre for Cancer Treatment
DG Regio	Directorate General for Regional and Urban Policy
EBITDA	Earnings before interest, taxes, depreciation and amortisation
EC	European Commission
EIB	European Investment Bank
EIRR	Economic Internal Rate of Return
ENPV	Economic Net Present Value
ESA	European Space Agency
ESF	European Science Foundation
ESFRI	European Strategy Forum on Research Infrastructures
EU	European Union
EUR	Euro
EXV	Existence Vale
FIRR	Financial Internal Rate of Return
FNPV	Financial Net Present Value
GHG	Greenhouse gas
HEATCO	Harmonised European Approaches for Transport Costing and Project Assessment
ICT	Information and Communications Technology
LHC	Large Hadron Collider
LRMSC	Long Run Marginal Social Cost
NACE	Statistical Classification of Economic Activities in the European Community
NASA	National Aeronautics and Space Administration
NOAA	National Oceanographic and Atmosphere Administration
OECD	Organization for Economic Cooperation and Development
PDF	Probability Distribution Function
Pr	Probability
QOV	Quasi-Option Value
QUALY	Quality-Adjusted Life Year
RDI	Research, Development, Innovation
TCM	Travel Cost Method
VOSL	Value of Statistical Life
WTP	Willingness-to-pay

Main notation

A	Market equilibrium
B_n	Non-use benefits
B_u	Use-benefits
C_u	Use-Costs
D	Demand curve
d	Market distortion
$\mathbb{E}$	Expected value
ex	Externality of patent
F	Value of knowledge spillover
Δ	Variation
ΔG	Project demand
H	Value of human capital formation
i	Index of goods/entities/individuals ranging from 1 to I
m	Multiplier of impact for knowledge output
MSV	Marginal social value of patents
n	Index for non-use values
O	Value of knowledge outputs
P	Social value of patents
p	Supply price
pv	Private value of patent
q	Demand price
R	Value of recreational benefits
r	Social discount rate
ref	Average number of references included in patents
S	Supply demand
s_t	Discount factor
t	Index for years, ranging from 0 to $\mathcal{T}$
$U(\cdot)$	Utility function
u	Index for use values
use	Average rate of usage of granted patents
v	Shadow price
X	Vector of project inputs, ranging from x to X
W	Willingness-to-pay for a visit
Y	Social cost of producing knowledge outputs
Z	Value of developing new/improved products, services and technologies
α	Set of multiplicative parameters representing the characteristics of the scientific community
Π	Profit
β	Parameter determining the shape of the curve that change according to the papers weights, distinguishing between excellent and mediocre papers

Foreword

This paper summarises the main findings and lessons learned on how to apply cost-benefit analysis (CBA) for research, development, and innovation (RDI) infrastructures drawing from a research project carried out by the University of Milan in partnership with the CSIL Centre for Industrial Studies. The study was supported by an EIB Institute grant (*University Research Sponsorship Programme – EIBURS)* and involved more than twenty researchers from a broad range of scientific fields[1].

After three years of research, the team developed a conceptual framework and applied it to two selected cases (i.e. the Large Hadron Collider (LHC) at CERN[2] and the National Centre for Oncological Treatment (CNAO) in Pavia (IT)[3]) to explore methodological challenges and further potential applications. A special issue of the journal, 'Technology Forecasting and Social Change'[4], is expected to be published in 2016 with articles by economists, physicists and other experts from several EU countries and from China.

In distilling and communicating the main lessons learned during the three years of research, it is important to stress from the beginning that this terrain is mostly uncharted. Although the conceptual model builds on principles firmly rooted in CBA tradition, its application to the RDI sector is still in its infancy. Hence, the approach adopted in this discussion paper is explorative and heuristic.

The concepts presented in the paper would benefit from further applications and testing beyond what has been possible to do in the specific framework of this research project. Future versions of this paper will take into account as best as possible any comments or new findings.

The structure of the paper is as follows. After presenting the rationale for using CBA and the main specificities of RDI infrastructures in the CBA perspective (Section 1), suggestions on how to perform the financial analysis of the RDI projects as a preliminary step (Section 2) and the socio-economic analysis (Section 3) are given (Section 4). Then, section 5 provides suggestions on how to perform a proper risk analysis and indications on how to effectively present the results of the analysis (because communication of results is important in a new field) and concludes.

[1] The full list of researchers is available on the project website at www.eiburs.unimi.it

[2] See Florio *et al.* (2015).

[3] See Pancotti *et al.* (2015).

[4] www.journals.elsevier.com/technological-forecasting-and-social-change

1. Executive Summary

1.1 Introduction

Governments, funding agencies and policy makers have high expectations on research, development and innovation (RDI) infrastructures in the context of science and innovation policies aimed at sustaining economic growth in the long term. The construction and operation of these often large and complex RDI facilities is increasingly costly and there is competition for public support. A wide range of approaches and methods are used in different institutional settings for the selection and prioritisation of such infrastructures. These include peer review of the scientific case, the development of national, international or sectoral roadmaps, and a number of quali-quantitative indicators of results. Yet, a consensus on the most appropriate methodology to assess the socio-economic long-term impact of major RDI projects is still missing. The objective of this discussion paper is to explore the applicability of the cost-benefit analysis (CBA) approach to this issue.

CBA is grounded in welfare economics, and its application to traditional infrastructures, such as transport, water, energy is firmly established, as revealed for example by a recent survey of OECD countries (OECD, 2015). More recently CBA have also been successfully applied to environment, education, cultural investment. Until now, however, the use of CBA to evaluate RDI infrastructures has often been hindered by the intangible nature and the uncertainty associated to the achievement of research results.

Recently, some attempts to develop a CBA theoretical framework for RDI infrastructures have been made in the context of the use of Structural Funds by the Czech government and JASPERS.[5] Moreover, for the first time after its previous four editions, the new Guide for the CBA of investment projects in the context of Cohesion Policy, recently adopted by the European Commission (2014) provides guidelines to appraise RDI projects, but also admits that – due to lack of experience and best practices – further steps are needed to improve the evaluation framework.

This discussion paper presents the results and the lessons learned on how to apply ex-ante CBA for major RDI infrastructures by a team of economists and scientists at the University of Milan and CSIL during a three-year research project supported by a EIBURS grant of the European Investment Bank Institute. Albeit the comprehensive conceptual framework presented in the paper builds on principles firmly rooted in CBA tradition, their application to the RDI sector is still in its infancy. The model has been applied on two cases in physics involving particle accelerators (the Large Hadron Collider (LHC) at CERN[6] and the National Centre for Oncological Treatment (CNAO) in Italy)[7]), but further applications and testing are needed to fine tune and expand the proposed appraisal techniques as well as to contribute to building a larger information base.

1.2 A CBA model for RDI projects

The core of CBA is an evaluation (ex-ante or ex-post) of the project intertemporal socio-economic benefits and costs, all expressed in units of a welfare *numeraire* (usually money in present value terms). The net effect on society is finally computed by a quantitative performance indicator (the net present value, or the internal rate of return, or a benefit/cost ratio). In line with the general CBA fundamentals, a CBA model of RDI should make use of: 1) shadow prices to capture social costs and benefits beyond the market or other observable values; 2) a counterfactual scenario to ensure that all costs and benefits are estimated in incremental terms relative to a 'without project' world; 3) discounting to convert any past and future value in their present equivalent; and 4) a consistent framework to identify social benefits by looking at the different categories of agents (producers, consumers, employees, tax-payers).

For the purpose of RDI project evaluation, it is convenient to divide social intertemporal benefits in two broad classes. On the one hand there are *use benefits*, accruing to different categories of direct and indirect users of the infrastructure services, such as e.g. scientists (insiders and outsiders), students starting their career within the facility, firms benefitting of technological spill-overs, consumers benefitting of innovative services and products, and general public visitors of the facility or those enjoying outreach activities. The identification of use-beneficiaries is project specific and must carefully avoid omissions or double counting of impacts. On the other hand, there are *non-use benefits*, reflecting the social value of the discovery potential of the RDI infrastructure, regardless its ex-ante predictable actual use. This is a measure of the social preference for pure discovery, akin to

[5] See Czech Ministry of Education, Youth and Sport and JASPERS (2009) and JASPER (2013).

[6] See Florio *et al.* (2015).

[7] See Pancotti *et al.* (2015).

social preferences for culture, or environment protection *per se*. The sum of these use and non-use benefits is then compared with costs. Whenever possible, the risks of forecasting errors should be taken into account by attaching probabilities to the values of each critical variable entering the model.

A significant feature of a CBA approach to RDI is the stochastic nature of the model. Consistently with best practice in the field, the project performance is assessed in probabilistic terms using a Monte Carlo simulation that approximates the probability distribution functions of the socio economic net present value (or other indicators), their cumulative distribution functions, the expected value, etc.

In a nutshell, the CBA model presented in this paper is intended to predict socio-economic benefits and costs of RDI projects in measurable form. While the model includes the measurable forecasting errors, it deliberately leaves aside what is intrinsically non-measurable. The model should be seen as a complement, not as a substitute, of the scientific case evaluation, financial and budgetary issues, managerial and strategic considerations, or political dimensions of investment in RDI, which are also obviously important. A preliminary financial analysis of the project in long-term cash-flow terms is helpful, but should not be confused with the social CBA.

1.3 Social Costs

As for projects in other fields, the main categories of costs associated to RDI infrastructure relate to the present value of capital, labour cost (including the labour cost of scientific personnel and the labour costs of other administrative and technical staff), other operating costs, such as materials, energy, communication, maintenance, etc., negative externalities, like air pollution or noise during construction and operations, and decommissioning.

However, when the infrastructure is designed to perform a range of different experiments and activities or the project consists of several inter-related but relatively self-standing components, delimiting the project borders and, in turn, its costs is challenging. If the analysis focuses on assessing a single experimental facility part of a larger complex, the costs that are shared by other experiments out of the scope of the analysis should be duly apportioned to the infrastructure under examination. Sunk costs should not be included in the computation of costs.

1.4 Social benefits

Traditionally, in economics, agents are classified according to their roles: firm owners, consumers, employees, tax-payers. These classifications are flexible, as in some cases producers of goods are also consumers (e.g. small farmers), employees are also tax-payers, shareholders are also firm managers, and so on. In CBA it is crucial to identify the beneficiaries in a way consistent with first principles of welfare economics.

Having identified the main beneficiaries of an RDI infrastructure, a list of typical benefits can be attached to each group. Depending on the project's nature, some of these benefits may accrue to different types of target groups. Also, the intensity of each benefit may be highly variable across the different typologies of RDI infrastructures. Hence, only a case by case study can design the appropriate research strategy.

1.5 Social benefits to firms

The following benefits to firms can often be identified and evaluation methods applied in relation to RDI infrastructure projects:

- The *development of new/improved products, services or technologies* has a socio-economic value measurable by the *expected incremental shadow profits* (i.e. after using shadow prices when needed for inputs and outputs) expected from their sale as compared to the without-the-project scenario;
- The *grant of a patent* has a marginal social value taking into account both the private value, i.e. the value from the patent holder point of view,and the externality, i.e. the knowledge spillover brought about by patents in generating a cascade of innovation;
- The creation of *start-ups and spin-offs or (and) an increase in their survival rate*: the economic value of this benefit is valued as the *expected shadow profit* gained by the created business during its overall expected lifetime compared with the without-the-project scenario. Whereas, if the RDI infrastructure contributes to increasing the survival rate of start-ups, then the benefit is valued as the *incremental expected shadow profit* attained by businesses that survive longer than in the without-the-project scenario

- The occurrence of *knowledge spillovers from the RDI project to third-parties* (businesses, professionals, public organisations), can be valued using alternative approaches (or a combination of them provided that double counting is carefully avoided) depending on the category of beneficiaries (i.e. incremental shadow profit; avoided costs, willingness-to-pay (WTP) for time saving);
- The *learning-by-doing benefit* for firms in the supply chain of a major RDI infrastructure, is valued through the incremental shadow profit expected by supplier companies thanks to the fact they have collaborated with the scientific and technical staff of the infrastructure and, in turn, have acquired new knowledge and technological skills;

1.6 Social Benefits to researchers and human capital formation

In general, employment is a social cost (except when there is very large unemployment). Therefore, the social benefit of employment has to be taken into account by exclusively using shadow wages, i.e. by considering that the opportunity cost of employing a person in the project under assessment is lower than that from using the same person for any alternative use.

However, RDI infrastructure projects have the mostly unique peculiarity that some producers of services are also their beneficiaries. Namely:

- Students and young scientists who will spend a period working within a major RDI infrastructure will earn higher human capital relative to their peers. The socio-economic value of this benefit is expressed as the expected *incremental lifelong salary* earned by such individuals over their entire careers compared with the without-the-project scenario;
- Scientists at the RDI facility produce knowledge, but are also users of such knowledge. The process is embodied in the production of knowledge outputs (i.e. technical reports, preprints, working papers, articles in scientific journals and research monographs) and their degree of influence on the scientific community in form of citations. The socio-economic benefit related to the production of scientific outputs can be valued using their *marginal production cost,* which is common practice in CBA for certain types of services, when market prices are not relevant and when WTP is not the appropriate empirical approach. Instead, the degree of influence of such outputs is reflected in the number of people that would cite it and valued through the *opportunity cost of time* employed by a scientists to download, read and understand someone else's output and decide to cite it. An important consequence of valuing scientific outputs at their marginal cost, which is mainly labour cost, is that to a certain extent scientific work pays for itself (an analogy is self-employment in subsistence farming where the benefit of the output – i.e., food – net of other costs, is exactly the value of the labour input). It is important to avoid the confusion, however, between the value of knowledge *outputs* (publications) and the value of *knowledge per se* embodied in such publications. The former is usually predictable, while the latter is often unmeasurable (the social value of producing and selling a book is unrelated to the social value of understanding its content and elaborating on it by the readers).

1.7 Social benefits to consumers of services produced by the RDI project

Benefits to consumers are highly project specific.

- They may derive from the use of the infrastructure's equipment and/or the provision of specific services to *external users* (e.g. industries, governmental bodies and other research teams). In this case, the socio-economic benefit is valued by either using the l*ong run marginal cost* of the services provided or estimating *external-users' WTP for the service*. Alternatively, when market prices are available and are supposed to be non-distorted, i.e. they reflect economic prices, the *nominal (market) price*s can be used.
- Also, benefits to consumers may derive from the practical application of a research effort (e.g. reduction of GHG and air pollutant emissions; improved energy efficiency; reduction of vulnerability and exposure to natural hazards; improved health conditions, or simply lower production cost and sale price, etc.). The methods to quantify and value these benefits depend on the types of new services or products made available by the infrastructure. However, these methods are generally based on the willingness to pay or avoided cost approaches, and are often well established in CBA.
- Other use benefits include the cultural effects enjoyed by both on-site and virtual visitors of the RDI project because of outreach activities. The expected marginal social value of this benefit is valued using the visitors' implicit willingness-to-pay for a visit. Concerning in-person visits, the standard way to estimate the WTP is using the travel cost method,

while a broadly used method to attach a monetary value to non-market goods such as virtual visits is contingent valuation;

1.8 Non-use benefits and the tax-payers: discovery as a public good

There are other social benefits to be considered, more elusive but nevertheless important. These are non-use benefits. While for applied research, development and innovation most benefits accrue to direct and indirect users (firms, consumers, researchers and students) for fundamental research it is usually impossible to identify who will be the ultimate beneficiaries of a discovery.

- If there is a potential but largely unknown future use-benefit, this can be defined a *quasi-option value* and while it is conceptually important to acknowledge its role, CBA methods are often unable to quantitatively determine it, even if research on the topic is ongoing. It is suggested to conservatively set to zero such value, except when the evaluator is confident of being able to make predictions on the economic value of applications of fundamental research.
- As the tax-payers ultimately foot the bill of some government-supported research infrastructures, it is appropriate to know their willingness to pay for their discovery potential. This is a non-use value of a public good, similar to the notion of existence value in environmental CBA. In principle, the social preference for pure knowledge *per se*, regardless the fact that it might find some use in the future, is empirically testable by stated preference techniques. Similarly to what is done in environmental or cultural economics for estimating the economic value of endangered species protection, preservation of natural resources, or conservation of cultural heritage assets, the contingent valuation methodology can be exploited to elicit the taxpayers' WTP for having a discovery, regardless of its actual or potential use.

1.9 The probability distribution of the economic net present value

Once the socio-economic benefits (including both use and non-use benefits) and costs associated with an RDI infrastructure have been identified, valued in monetary terms and discounted using a social discount rate, the effect on society is finally computed by a quantitative performance indicator (the net present value, or the internal rate of return, or a benefit/cost ratio).

Whenever possible, the risks of forecasting errors should be taken into account by attaching probabilities to the values of each critical variable entering the model. Hence, consistently with best practice in the field, the project performance is assessed in probabilistic terms using a Monte Carlo simulation that approximates the probability distribution functions of the Economic Net Present Value (or other indicators), their cumulative distribution functions, the expected value, etc.

1.10 Conclusions

The CBA model presented in the discussion paper provides a comprehensive framework for ex-ante assessment of major RDI infrastructures, consistent with the general applied welfare economics fundamentals, but innovating the field in several ways.

The model is also novel and heuristic because it intends to apply principles firmly rooted in the CBA tradition into a new uncharted field. The application of the model on two pilot case studies in physics involving particle accelerators, respectively in pure science and medical research, has contributed to explore its empirics. Therefore, this discussion paper is intended to sow the seed of further applications and testing to fine tune and expand the currently methodologies and techniques.

Experience in other fields of CBA, such as environmental and cultural economics, suggests that several years of practical testing are needed before new ideas are embodied in an accepted paradigm by practitioners. It is hence needed to be experimented in different RDI domains, with their specificities, the empirical analysis.

2. Motivation and Principles

2.1 Increasing need for accountability

Policy makers have growing expectations that RDI infrastructures are essential components of technological and scientific progress (EC, 2010; ESFRI, 2010; Technopolis, 2011; ESF, 2013). Hence, the stakes associated with the selection and evaluation of such infrastructures are high.

Traditionally, the selection and appraisal process of RDI projects relies on science's own internal quality control mechanisms and the policy context. Typically, these mechanisms involve a peer review process that assesses the 'science case', sometimes complemented by a 'business case' or considerations related to the socio-economic impact (Feller, 2013). Although this approach is usually efficient and fair, it is not suitable for appropriately assessing the socio-economic effects of a project. The scientific or business cases are complementary evaluation tools but are not necessarily correlated to the socio-economic impact of a project. For this reason, specific evaluation tools and methods are needed.

Recently, a more strategic approach to RDI investments has been promoted by international practice, with the development of roadmap exercises to prioritise RDI infrastructures at the national or European level (ESFRI, 2008; OECD, 2008; Research Council UK, 2010). Typically, roadmaps assess RDI infrastructures according to a set of quali-quantitative criteria ranging from scientific and technological excellence to socio-economic impact indicators and governance and financial aspects. In some cases, the approach also includes the consideration of risk factors. However, no consensus exists on a unique evaluation model; instead, a variety of different experiences exist (Pancotti, *et al.*, 2014). This lack of consensus hinders the possibility to systematically compare the impact of different projects that may compete for scarce funding, or to compare ex-ante, on-going, and ex-post evaluations, as suggested by the best international practice for project appraisals of major infrastructures. Although roadmaps are relevant strategic and planning tools, they are not designed to provide a socio-economic impact evaluation framework, consistent with applied welfare economics principles.

Against the demand for credible methodologies to assess RDI infrastructures, cost-benefit analysis (CBA) is considered a promising candidate. CBA emerged from more than one hundred years of intellectual history (Dupuit, 1844 and 1853; Pigou, 1920; Little and Mirrlees, 1974) and is now a recognised evaluation technique (Florio, 2014). Currently, CBA is widely adopted by international institutions and governments to assess the socio-economic profitability of investment projects in many fields.[8] Although already advocated by some international and national organisations, even with a number of caveats and possible adaptations (ESA, 2012; EIB, 2013; OECD, 2015), up to now CBA has not been systematically adopted on a broad scale in the RDI sector.

Until recent years, the development of CBA in the RDI field was hindered by the perception of the unpredictability of the long-term benefits of knowledge (Martin and Tang, 2007). Actually, the nature of knowledge creation – the typical output of RDI projects – is such that the effects of a discovery may appear in the very distant future, long after the decommissioning of the RDI infrastructure. The uncertain impacts of the RDI infrastructure on social welfare, combined with the difficulties in measuring them, have probably slowed down the diffusion of CBA in the RDI sector. However, a renewed interest is observable in recent years because the stakes associated with RDI infrastructure selection and ex-ante appraisal have increased[9].

Earlier attempts to develop a CBA theoretical framework in the field of RDIs was initiated by the Czech government in 2009 and further expanded by the JASPERS team at the European Investment Bank[10]. On the basis of the experience gathered in the 2007–2013 programming period, JASPERS produced a staff working paper as preliminary guidance for the application of the CBA approach into practice in the RDI sector[11]. Another recent contribution is provided by the European Space Agency (2012), which proposed a methodology called 'SCBA-plus' to establish the impact of space programmes. The methodology consists of a combination of social cost benefit analysis and multi-criteria analysis. A recent survey by the OECD (OECD, 2015) showed that some governments are using CBA in the RDI field.

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[8] See, for instance, Adler (1987); Atkinson *et al.* (2006); EC-EIB (2005); EC (2007); Economics and Development Resource Center (1997); Pearce *et al.* (1994); WHO (2006); and Asian Development Bank (2013).

[9] For example, in the UK, the Science and Technology Facilities Council is committed to mobilising a methodology for to make a difficult decision on where to discontinue funding in a context of a 'flat-cash' budget (Technopolis, 2013).

[10] Czech Ministry of Education, Youth and Sport and JASPERS (2009). Background methodology for preparing feasibility and cost-benefit analysis of R&D infrastructure projects in Czech Republic, supported by the Cohesion Fund and the European Regional Development Fund in 2007–2013.

[11] JASPERS (2013). Project Preparation and CBA of RDI Infrastructure Project, Staff Working Papers, JASPERS Knowledge Economy and Energy Division.

The approach proposed in this discussion paper draws from and further develops the mentioned previous work and is consistent with the general methods suggested in the updated EC Guide for CBA (European Commission, 2014). Hence, the paper takes advantage of the substantial experience gained by researchers and practitioners worldwide on the evaluation of infrastructures in a range of sectors and tries to apply the lessons learned in other contexts to the specific challenges posed by RDI infrastructures. The proposed approach should be intended to complement and not substitute for other evaluation methods, including peer review assessments, road mapping, qualitative evaluation of socio-economic impact and monitoring of performance indicators.

2.2 The perspective of social cost-benefit analysis

Social CBA is grounded in welfare economics, according to which the welfare of a society depends on the aggregate individual utility of all of its members. In a welfare economic frame CBA arises as the solution for the government's planning problem of the constrained optimisation of a social welfare function (Drèze and Stern, 1990; Florio, 2014).

CBA theory and application have evolved over time and have undergone different phases of experimentation, consolidation, and diffusion in a variety of institutional settings and sectoral traditions. Yet, a number of key features and principles offer a good framework for a solid and systematic approach to RDI project appraisal and selection. In particular, these features and principles are as follows.

- Social CBA is a tool aimed at informing decision making on the economic viability of investment decisions by quantitatively expressing all of the costs and benefits to society. The net economic benefit to society is used as the performance criterion. Costs and benefits are expressed through a monetary metric, but any welfare *numeraire* or appropriate accounting unit also works. Against the existing evaluation approach for RDI projects, CBA offers a tool to systematically compare both costs and benefits on a unique accounting basis.
- A long-run timeframe is adopted to assess the social welfare change attributable to it, implying the identification of a proper time horizon and the consideration of long-term sustainability.
- CBA makes a clear distinction between social welfare effects and financial effects. The former are expressed in accounting prices that convey the social opportunity costs of a project's inputs and outputs ('shadow prices'), whereas the latter are prices adopted and observed on the market. CBA makes use of shadow prices and uses market prices only to assess the financial viability of a project (see below).
- Costs and benefits are considered incrementally, which requires a systematic comparison between the project option and a proper counterfactual ('with' and 'without the project' scenarios) (see *Box 1*).
- The key strength of CBA is that it produces information on the project's net contribution to society's welfare, synthesised into simple indicators, such as net present value. This approach leads to the possibility of comparing several investment options or past expectations with actual outcomes.

Box 1. Choosing a proper counterfactual scenario

The incremental approach requires that the costs and benefits of the proposed project are estimated in incremental terms within a counterfactual scenario (without-the-project). This method serves to grasp the 'net' change, i.e. the change specifically attributed to the intervention analysed. The choice of the counterfactual scenario requires a careful examination and implies defining what would happen in the absence of the project. In-depth discussions with science specialists involved in the project design and with independent professionals capable of providing sufficiently disinterested judgments are fundamental to choosing a proper counterfactual scenario. The following two broad options are available.

- For a completely new facility ('green field'), the without-the-project scenario is usually a 'zero-based' scenario. In other words, the incremental scenario coincides with the 'with-the-project' scenario.
- For investments aimed at improving an already existing RDI facility, the counterfactual should include the costs and benefits to operate and maintain it at a level that keeps it operable (this scenario is referred to as 'business as usual' or 'do-nothing') or even small adaptation investments that were programmed to occur anyway (do-minimum).

Examples of green field RDI facilities are the National Hadrontherapy Centre for Cancer Treatment (CNAO) based in Pavia, the Jules Horowitz Reactor (JHR) built on the Cadarache site in France. Examples of incremental RDI facilities are the High Luminosity Large Hadron Collider at CERN and the upgrade of the European Synchrotron Radiation Facility in Grenoble.

2.3 Key features of RDI infrastructures

Given the wide variety of facilities that are generally referred to in this field, no established and agreed definition of RDI infrastructures exists in the literature and in policy documents[12]. However, a number of constituent features of typical RDI infrastructures exist that lend themselves particularly well to be assessed using CBA. These features are as follows.

- Based on tangible assets: The assets can be either single-sited, mobile or distributed. Most RDI infrastructures, such as particle accelerators, telescopes, and technological platforms, are single-sited, i.e. a unique facility or a combined set of infrastructures and equipment located in a single physical location, as defined by ESFRI (2008). However, mobile[13] and geographically distributed facilities also exist. The latter includes for instance grid computing systems or seismographic stations consisting of a network of infrastructures located in different areas but with a strong functional relationship among all of their parts.[14] Finally, some RDI infrastructures provide their services in electronic form, i.e. through storage, transmission, and elaboration of coded information. High performance ICT-based technologies can be essential for an RDI infrastructure to making particularly complex computations and simulations, thus actually producing new knowledge and, for this reason, are to be distinguished by traditional ICT infrastructure.[15]

- High-capital intensity facilities: Capital expenditures[16] overcome operating costs, i.e. they represent a large share of the total present value of the project cost. Hence, different from RDI programmes, once the financing decisions are made, discontinuing such facilities before the full materialisation of their benefits becomes expensive.[17]

- Major facilities: They require substantial capital investments in infrastructure. For example, in the field of EU cohesion policy, a major project is conventionally defined as requiring a total investment cost in excess of EUR 50 million[18].

- Long-lasting facilities: The economic life of RDI infrastructures is not different from that of more standard infrastructures. Generally, these facilities remain operational for more than two decades after their construction. In some domains, research infrastructures only develop their full scientific potential if a long-term data series can be generated

[12] See, for instance, ESFRI (2008); Horlings, E. and Versleijen, A. (2008); JRC-IPTS (2002); Research Council UK (2010); and Technopolis (2011).

[13] An example is provided by research vessels.

[14] Conversely, a network of mutually-independent RDI infrastructures, each providing its service without depending on the service provided by another facility in the same network, is not accounted for as a single distributed RDI facility but instead as a number of single-sited infrastructures.

[15] Examples are supercomputers and grid computing, which consists of computer resources specifically developed to process big data and produce outputs for scientific use. On the contrary, it can be argued whether collaborative ICT infrastructures where large volume of algorithms for data pre-processing, statistical analysis and annotation are integrated and chained to build ad hoc workflows for users, qualify as RDI infrastructures per se. ICT tools for integration of datasets can be a component or an output of a RDI infrastructure. The collaborative aspect can be important in terms of spillover effects since it allows an easier exchange of research and innovation outputs among the scientific communities; at the same time, the collaborative nature of different RDI infrastructures could pose some challenges in terms of benefits appropriation, since the boundaries of research and innovation outputs become blurred and their ownership difficult to be clearly attributable.

[16] They include both fixed capital and initial human capital formation expenditures.

[17] As a general remark, in the paper we consider the investment as a one-shot decision but in practice decision makers face options of expanding, deferring or abandoning the investment. RDI infrastructure projects are actually embedded in a sequential process with multiple stages and mile-stones associated with certain risk. Along a decision tree risks vary according to the likelihood of achieving different end points, taking these risks into account involves managing different discount factors. The theory of option prices provides a solution to manage this situation by means of a trick based on adjusting each state's probabilities in accordance with the 'risk neutral' discount factor. For a discussion of this issue see EIB (2013), Jägle (1999), Luehrman (1998), Courtney et al. (1997).

[18] As per article 100 of Regulation (EU) No 1303/2013.

and recorded (Wissenschaftsrat, 2013). The adoption of a long time horizon is necessary for a comprehensive appreciation of their performance.

- Facilities with the objective of producing social benefits through a generation of new knowledge and innovation for a variety of users: RDI infrastructures are realised with the main purposes of acquiring new knowledge in a given scientific or technological field and/or using the stock of new knowledge to devise new applications or produce innovation. A typical distinction is made between the following infrastructures.
  - Infrastructures for fundamental research, such as a large telescope, are meant to support basic research, i.e. undertaking theoretical or experimental work primarily to acquire new knowledge on the underlying foundations of phenomena and observable facts, without any direct practical application or use in view ('curiosity-driven').
  - Infrastructures for applied research and technological development are meant to support the acquisition of new knowledge for a potentially well-identified practical purpose, i.e. the development of new products, processes, or services (e.g. quantum computing or human genomics).
  - Innovation infrastructures, such as a laboratory within a pharmaceutical firm or working for a consortium of firms, aim to combine new knowledge and technology for the future commercial exploitation of newly developed applications.
- Potentially supporting multiple experiments or testing: In the RDI sector, some facilities are destined to remain unique at a regional, national, or even global level because a second facility is too expensive or because the number of users is not large enough. In these cases, the preferred setting usually entails arrangements for different teams of users of the same infrastructure and exploiting its features to perform different experiments or tests, either over time or at the same time.

Although such features distinguish RDI Infrastructures from traditional RDI programmes and initiatives, they are instead shared by traditional infrastructures in other sectors (e.g. environment and transport). For this reason, the use of a CBA framework seems particularly appropriate[19].

[19] For the same reason, examples of research infrastructures for which the justification of a CBA framework is less robust are the construction or modernisation of buildings with primarily educational purposes; knowledge-based resources such as collections, archives, or surveys, for which the service they provide – i.e. the collection and elaboration of data *per se* – is usually more labour than capital intensive; and relatively small RDI projects with capital costs of millions of Euros.

Figure 1. Examples of major RDI infrastructures

Fundamental research infrastructures	•Linear particle accelerators, such as the Stanford Linear Accelerator Center (SLAC) operated by Stanford University in the United States; •Synchrotrons, such as the Large Hardon Collider (LHC) operated by CERN in Geneva; •Telescopes, such as the 4.3-meter Discovery Channel Telescope operated by the Lowell Observatory in Arizona; and, •Satellite and aircraft observation facilities, such as the Hubble Space Telescope operated by Space Telescope Science Institute.
Applied research and development infrastructures	•Clean rooms for the study and development of new materials or nano-electronics, such as those operated by the Fraunhofer Institute for Photonic Microsystems IPMS in Dresden; •Syncrotrons for hadrontherapy, such as the National Center for Oncological Hadron Therapy (CNAO) in Pavia; and, •University laboratories for applied research and testing, such as the Laboratory of Applied Mechanics & Vibrations of University of Patras.
Innovation infrastructures	•Technology parks, such as the BioTechPark Freiburg in Germany; •Science parks, such as the AREA Science Park in Trieste; •Business incubation centres, such as the ESA's Business Incubation Centres across European countries; and, •Innovation centres, such as the IdE Institute decentralized Energy Technologies in Germany.

Source: Authors

2.4 Categories of potential beneficiaries

In economics, agents are traditionally classified according to their roles: firm owners, consumers, employees, tax-payers. These classifications are flexible, as in some cases producers of goods are also consumers (e.g. small farmers), employees are also tax-payers, shareholders are also firm managers, and so on.

From the CBA perspective, it is crucial to identify the potential beneficiaries (or losers) of a project. Consistently with first principles of welfare economics and because of the variety of possible services delivered by major RDI infrastructures, at least six groups of social agents exist whose welfare is potentially affected by a RDI project.

Table 1. Classification of potential beneficiaries of an RDI infrastructure

Type of agent	Description
Businesses	Businesses include spin-offs and start-ups, small and medium enterprises, and large enterprises that directly enjoy the services provided by the project and/or benefit from indirect spillover effects, particularly through procurement and supply chain learning effects.
Employees	Scientists and researchers produce knowledge, but are also are direct users of the RDI facility. They encompass both inside staff and outsiders, who are the rest of the research community, including those working in other fields that may use the evidence provided by the experiments to produce further knowledge and innovations. Young professionals, junior researchers, and students who will spend a period working within the RDI infrastructure. They include, for example, post-doctoral researchers, early career researchers who use the RDI facility to carry out their own studies/tests, and students, usually at graduate level, involved in training or the preparation of their dissertation or who have access to the facility through a training programme.
Consumers	Consumers of goods or services produced by RDI projects. They may include, for example, patients associated with medical treatment provided at a health research infrastructure and residents of a region in which major risks such as floods, earthquakes, and fires are better monitored/forecasted because of the research developed by observatories, stations, or satellites, among others. The general public involved in outreach, which includes onsite visitors to the facility and virtual visitors on websites and social networks; media exposure is also the effect of outreach activities and people derive utility from being informed about research and technological progress;
Taxpayers	Non-use beneficiaries, such as most tax payers who fund RDI infrastructures without directly using it and people who do not plan to visit (personally or virtually) the infrastructure. Such individuals may derive some utility from the mere fact that they appreciate that scientific discoveries and technological progress are possible because of the infrastructure; these potential beneficiaries of knowledge create a global public good with an intrinsic non-use value.

Source: Authors

The conceptual model developed stems from the consideration that the recognition and proper identification of actual and potential beneficiaries is an essential ingredient of the assessment. Indeed, different categories of target groups are associated with different types of benefits and externalities, thus estimating the present and future demand for the infrastructure. The infrastructure's outputs for each of the identified groups of beneficiaries are the starting point of the analysis. Regardless of the estimation technique chosen, the underlying assumptions (parameters, coefficients, and values) that show that a critical mass of users (and non-users) exists need to be stated transparently and tested in the risk assessment.

In most cases, the previous list of six groups (see Table 1) likely covers the universe of potential beneficiaries of RDI projects. The list is based on the consideration that the 'demand side' of the evaluation is correlated with benefits, whereas the 'supply side' is correlated with social costs. Because most RDI services are not marketed, some confusion may exist over the agents and determinants of supply and demand. However, these mechanisms are built in any project. In a CBA framework, the willingness to pay for the service by agents ultimately determines its social value, and each of the six groups that we mention 'has standing' in the project from this perspective: firms because RDI potentially creates value to their owners; scientists and young researchers because of the reputational effects and human capital formation; service beneficiaries because of the avoided costs and/or better quality of life; and the general public because of the direct cultural effects or the willingness to pay for a public good. Instead, employment, procurement, use of land, and others are items on the cost side. In the rest of this paper, we focus on the main items that enter into an evaluation, even though additional impacts may need to be considered in specific projects.

2.5 The model

The model on which the rest of the paper is built takes the form of a simple yet comprehensive equation (for slightly more technical details see Florio and Sirtori, 2014):

$$\mathbb{E}\,(ENPV_{RDI}) = \mathbb{E}(EPV_{B_u}) + \mathbb{E}(EPV_{B_n}) - \mathbb{E}(EPV_{C_u})$$

In this frame, the social CBA exercise consists of forecasting, in incremental terms, the expected economic net present value of the RDI infrastructure projects ($\mathbb{E}(ENPV_{RDI})$), defined as the sum of the expected net present value of economic benefits associated with any actual or predictable practical use of the infrastructure services ($\mathbb{E}(ENPV_{Bu})$) and the additional expected value of discovery (new knowledge) for which a possible use is not yet identified ($\mathbb{E}(ENPV_{Bn})$) but for which a social value can be empirically estimated (non-use value), minus the expected net present value of the costs. In other words, our approach breaks down intertemporal benefits into two broad classes – use and non-use benefits – and compares these benefits with costs, taking into account the probability density functions attached to the determinants of each critical variable entering into the model.

In our framework, both fundamental and applied research in principle can be addressed, with the non-use benefit being often negligible for the more applied innovation projects at one extreme, and significant benefits coming from non-use value at the other extreme of fundamental research.

Three distinct concepts are included in our approach:

- the *expectation* operator implies that all critical variables are treated as stochastic;
- *economic value* indicates that our valuation uses shadow prices to capture social benefits beyond their market or financial value; and,
- the *net present operator* implies that any past or future value is converted into its present equivalent and costs are treated as negative benefits.

Different from prior literature, one contribution of the present approach is the consistent identification of the social benefits of the RDI infrastructure and the provision of a comprehensive framework to evaluate and combine them to obtain a synthetic quantitative measure of social benefit. In a CBA frame, carefully identifying different types of beneficiaries is necessary to apply concepts and empirical methods appropriate for each of such types and to avoid double counting the benefits.

Another advantage of relying on a CBA framework to assess RDI infrastructure is that, when focusing on social benefits, the analysis is often developed starting from a preliminary financial analysis (European Commission, 2014). The financial analysis is a useful management tool for verifying the long-term financial sustainability of the project.

As mentioned, the proposed CBA model suggests that all critical variables are expressed in terms of expected values. This suggestion implies conjecturing on the probability distribution functions of quantities and accounting prices (i.e. empirical proxies of unknown shadow prices) rather than using their punctual 'best guess' values. Given the large risks implicit in RDI projects, framing ENPV in terms of probabilities draws from the consideration that risk is measurable, whereas radical uncertainty is not (common sense often confuses the two concepts). From a heuristic perspective, a bold but useful step is to set to zero the value of what is radically uncertain.

The presentation of the approach consists of providing a structured discussion around three building blocks – CBA theory, empirical approaches, and examples. This presentation structure ensures a balance of conceptualisation and practical shortcuts (purely illustrative) when presenting an experimental framework.

The following sections describe in detail the steps of a CBA for RDI infrastructures. Although reference is made to the DG REGIO Guide (European Commission, 2014) for the standard approach to CBA, the aim of this paper is to illustrate how individual steps need to be adjusted to account for the specificities of RDI infrastructures.

3. Financial analysis in the RDI field

A clear difference exists between the socio-economic impact of an RDI project and its financial performance. The latter is carried out from the point of view of the project promoter and aims primarily to assess the project's sustainability. Financial performance is preparatory to the economic appraisal, which instead assesses the project's worthiness to society (at the global, country, and regional levels as appropriate). More specifically, the financial analysis is useful to determine the costs and revenues (if any) arising from the project over the reference period and to verify whether the projected cash flow ensures adequate operation of the infrastructure and its financial sustainability in the long term.

In this section, after briefly discussing the proper unit of analysis, the typical cash inflows and outflows to be considered for RDI projects are presented. In closing, the financial performance and the sustainability criteria are considered.

3.1 Unit of analysis, project borders, and cost apportionment

A useful step before carrying out the financial (and economic) analyses of a RDI infrastructure is to identify the object of the analysis. In principle, the appraisal should focus on all of the components that are logically connected to the attainment of the intended objectives[20]. In the appraisal phase, the unit of analysis is typically related to the financing decision; however, in some cases, a mismatch may occur between funding and project identification (for example, when funding is broken down in different decisions over time or across parts of a project). Delimiting the borders of a RDI infrastructure project is challenging when the infrastructure is designed to perform a range of different experiments and activities or when the project consists of several interrelated but relatively self-standing components. For example, the LHC is a combination of an accelerator system (itself composed of several accelerators) and detectors, each managed by international collaborations of scientists and laboratory staff in various combinations.

Depending on the specific nature of the infrastructure and the scope of the analysis, for multi-purpose RDI facilities, the project analyst could either focus on assessing the costs and benefits of a single experimental facility or take into account the costs and benefits related to both the hosting infrastructure and all hosted experiments. If the former approach is adopted (as in Florio *et al.* 2015), the costs related to the common facilities and that are shared by other experiments out of the scope of the analysis should be duly apportioned to the infrastructure under examination. Similarly, for distributed facilities, the project analyst should ascertain whether synergies and functional relationships among the facility components are such that they justify the assessment of the entire infrastructure as a single unit of analysis[21]. Otherwise, each project component should be appraised independently.

3.2 Typology of costs and revenues

Costs are defined as cash out-flows directly paid to build, operate, maintain, upgrade the RDI infrastructure.[22] Although costs disaggregation is project-specific, common categories of financial costs, including investment and operating costs that are generally related to RDI infrastructures, are presented in Investment and operating costs. The typical spending profile and cost distribution over time of different categories of the RDI infrastructure show a double peak, as illustrated in Illustrative spending profile and cost distribution over time of a single-sited RDI infrastructure.

[20] For a further discussion on the issue, see Belli et al. (2001); European Commission (2014); European Investment Bank (2013); Jenkins et al. (2011); and Florio (2014).

[21] See OECD (2014a) to further explore the topic of internationally distributed research infrastructures.

[22] In line with the economic theory, every factor of production (capital, labor, knowledge) has an associated cost. More specifically, in accounting terms, each resource used in a project, enterprise, etc. is associated with a monetary value. This monetary market value is taken into account in the financial analysis. Instead, in economic terms, each resource has an opportunity cost, which is the value of the next best economic alternative foregone due to the chosen use a determined resource. The opportunity cost of resources is considered in the economic analysis.

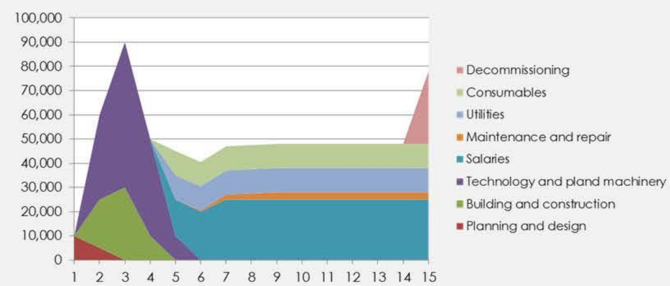
Box 2. Investment and operating costs

Investment costs	Operating costs
Planning and design	Scientific, technical, and administrative personnel
Land acquisition	Ordinary maintenance
Construction of buildings and plant	Material for the operation and repair of assets
Construction of plant and machinery	Utilities consumption
Machinery and equipment purchase	Services purchased from third parties
Utilities consumed during the construction phase (e.g. energy and waste disposal)	Rental of machinery
Start-up costs	Quality control
Licenses acquisition	Environmental protection measures
Replacement costs	General management and administration
	Property rights
	Promotional campaigns and other outreach expenditures
	Decommissioning

The design phase of a RDI infrastructure can be very long[23]. In addition, new facilities are sometimes developed in the same location as that of previous infrastructures and experiments, to some extent taking stock of the existing assets. Costs incurred before the start of the appraisal period, such as costs for feasibility studies undertaken at an earlier date or construction costs already sustained for a previous project, are *sunk costs* and excluded from the investment costs in an ex-ante project analysis. Similarly, *in-kind contributions*, i.e. goods, services, and staff provided in kind by external parties for the construction or operation of the project, are not considered in the financial analysis from the promoter's perspective because they do not represent actual cash flows. However, in some cases, a consolidated financial analysis across different funding or management bodies may be helpful.

Box 3. Illustrative spending profile and cost distribution over time of a single-sited RDI infrastructure

The overall spending pattern shows a relatively large investment peak during construction, a quasi-flat spending period during operation, and followed by a new peak for decommissioning. For a major upgrade during operation, another investment peak would have been visible. The distribution of costs during construction shows that civil engineering and technical hardware costs represent the vast majority of spending during the investment phase. Salaries, consumables, and utilities are the main expenditures during the operation period.



Source: Authors based on RAMIRI online handbook (http://www.ramiri-blog.eu/)

Revenues are defined as cash in-flows directly paid by project users for the services from which they benefit. Revenues can vary significantly from one project to another in relation to the specific type of services delivered by the infrastructure. Possible revenues are listed in ***Errore. L'origine riferimento non è stata trovata.***.

23 For instance, the Future Circular Collider study at CERN started in 2014 (see www.fcc.web.cern.ch) for an infrastructure proposed to follow the LHC around 2040.

Box 4. Revenues

- Sales of material, products, and equipment
- Sales of consultancy services
- Licence revenues gained from patent commercialisation
- Revenues from industrial research contracts and pre-commercial procurement contracts
- Research grants involving a transfer of ownership of a specific research output
- Entry fees to the laboratory and to use research equipment charged to researchers and businesses
- Rent of space
- Spin-off equity return to investor
- Student/Master/PhD fees
- Revenues from individuals using the research outputs (e.g. patients receiving innovative treatment)
- Revenues from outreach activities to the broader public (e.g. bookshop sales, entrance tickets)

The prediction of costs and revenues is an important step to prevent budgetary imbalances, which may affect the project's ability to generate the desired socio-economic effects. For instance, a technology park, for which forecasted operating revenues are inadequate to recover the initial investment and cover the expected operating costs, may risk halting its activities at a given moment. Unless other sources of financing are found, such a stoppage would imply that the desired effects on local businesses in terms of knowledge and technological progress will not materialise.

3.3 Dealing with inflows from research contracts and grants

Different from development and innovation activities that are expected to recoup their investments through future profits – particularly if carried out by businesses – infrastructure and experiments in fundamental research are typically supported by government funds or donations. This broad dualism involves different approaches to accounting for financial inflows. In particular, whether a financial inflow, particularly if granted by a public institution or agency, represents a source of financing or operating revenue for the project should be carefully assessed.

According to the DG Regio Guide (EC 2014, Chapter 7), public research contracts or contributions granted through either competitive or non-competitive arrangements should be considered operating revenues only if they are payments against a service directly rendered by the project promoter. Typically, this condition is verified when the ownership of the expected research output is transferred to the contracting public entity and does not remain with the RDI institution. Otherwise, these financing sources should be considered as transfers from state or regional budgets. As such, they should not be included as revenues but should account for the verification of the project's financial sustainability. This approach has consequences for the computation of financial performance indicators; see the next section.

Box 5. Operating revenues vs financing sources

Examples of flows considered operating revenues for the project:

- grant awarded by a national/regional public agency to a public research body, but in fact directed to the development/delivery of a new product/service commissioned by the agency; and,
- contributions paid by technology-based companies involved in co-development of equipment, software, and services to be able to use them as out-of-the-box products in the future.

Examples of flows to be considered financing sources for the project:

- grants from European/national/regional research funding frameworks (e.g. Horizon, 2020);
- loans from banks or financial institutions acting as intermediaries of public bodies;
- regular or exceptional donations from state agencies; and,
- donations from charitable entities and philanthropic organisations or individuals.

3.4 Financial profitability

An investment's financial profitability is the ability of a project to generate returns on the resources invested regardless of the sources of financing (loans, private equity, or grants).

The financial return on an investment is calculated using simple performance indicators, the financial net present value (FNPV), and the financial internal rate of return (FIRR). The former is expressed in monetary terms and is the discounted sum of the net financial flows for the entire time horizon. The latter is defined as the financial discount rate[24] that produces a zero FNPV.

A project with *positive financial performance* is associated with a positive FNPV, meaning that the total discounted inflows exceed the total discounted outflows. Under certain technical conditions[25], a FIRR higher that the reference financial discount rate provides the same information. Conversely, a project with *negative financial performance* is associated with a negative FNPV (and usually with a FIRR lower than the reference discount rate).

Frequently, financial indicators are used to set the correct volume of public support to be committed to welfare-improving projects (Florio, 2014), which require the contribution of public funds. For example, the European Commission allows for co-financing through grants only if the proposed major project is not financially profitable[26], i.e. the FNPV is negative and the FIRR is lower than the discount rate used for the analysis[27]. **Errore. L'origine riferimento non è stata trovata.** presents in anonymous form the financial performance indicators of a sample of RDI infrastructure projects co-financed by the European Commission.

Table 2. Examples of financial performance indicators of a sample of major projects co-financed by the European Commission during 2007–2013

Country	Field	FIRR	FNPV	Reference period
Germany	Innovation business Incubator centre	-63.0	-16,171,681	15
Poland	Materials and biomaterials	3.9	-2,800,501	15
Czech Republic	Laser infrastructure	-45.1	-171,530,005	22
Czech Republic	Biotechnology and biomedicine	-30.0	-124,941,750	15
Poland	Biological and chemical sciences	-3.9	-12,349,562	15
Lithuania	Physical and technological sciences	-12.5	-29,878,183	15
France	Advanced engineering materials	-33.0	-102,161,236	15

Note: The reference financial discount rate adopted is 5% for all projects except for the Lithuanian project, which used an 8% rate.
Source: Authors based on EC Major Project database 2007–2013. Data extraction concerns a selected category of investments (i.e. RDI infrastructure and centres of competence in a specific technology), as per annex IV of EC regulation 1023 (2006).

RDI projects with potential profitability are regularly assessed by venture capitalists.[28] Clarifying the difference between CBA and the role of venture capital project analysis is useful (see
Venture capitalists' investment decision).

[24] This rate reflects the opportunity cost of capital from the perspective of financial investor(s) and is used to discount financial flows to estimate the investment's profitability indicators. The financial discount is valued as the loss of income from an alternative investment with a similar risk profile and is estimated by considering the return on an appropriate portfolio of financial assets lost from the best alternative investment, the real return on government bonds, or the long-term real interest rate on commercial loans.
[25] The condition is that the net benefits do not change sign during the life of the project (e.g. because of high decommissioning costs). Otherwise, more than one interest rate value may make the NPV equal to zero. Additionally, the IRR cannot be calculated when time-varying discount rates are used.
[26] We do not consider the case of financial instruments.
[27] In contrast, economic performance should be positive (see section 5.1).
[28] It must be acknowledged that, in some cases, the RDI infrastructures are involved in a transitioning process from the public sector to the private one or the venture capital arena.

Box 6. Venture capitalists' investment decisions

To screen investment opportunities, venture capitalists use a broad range of accounting and non-accounting information. Examples of information sources are business proposal, contracts with other venture capitalists, interviews with the entrepreneur, interviews with potential investors, and statistical information services (see Wright and Robbie, 1996; Manigart et al., 1997). The collection and analysis of information – the due diligence process – is needed to gain a thorough understanding of all business aspects.

The principal aspects considered by venture capitalists when looking for promising investments include[29]:

- viability of the product or service;
- potential for sustained growth of the company;
- efficient management team for efficient control and operation of the company;
- a balance between risk and expected profits;
- and justification of venture capital investment and investment criteria.

Additionally, the screening activity involves a variety of valuation techniques to determine the profitability of venture capitalists' investments, ranging from standard valuation methods based on discounted cash flow analysis (e.g. Brigham et al., 1999; Brealey and Myers, 2000) or the earnings multiple and the value of a company's assets, to the most innovative approaches based on option pricing theory (e.g. Seppä and Laamenen, 2001). The latter with respect to more traditional methods seems to better handle uncertainty. For a review, see Manigart et al. (2000), which examined the valuation methods used by venture capitals in five different countries[30].

3.5 Financial sustainability

A project is financially sustainable when the financial sources (including both operating revenues and any other sources of financing) are able to cover the expenditures (including investment costs, operating costs, reimbursements and interests on loans, taxes, and other disbursements) year-by-year. Hence, if the cumulated net cash is negative even for one year, the project is not financially sustainable. In this case, the project promoter is expected to demonstrate the capacity to raise additional sources of financing to cover the costs in each year of the time horizon.

In the RDI context, a number of factors influence long-term sustainability, which is only partially related to a sustainable funding profile. In particular, attracting scientific talent or operating in a field gaining scientific relevance is usually the underpinning for long-term sustainability. Thus, financial sustainability should be considered together with other sustainable criteria, as discussed in Long-term sustainability of the RDI infrastructure.

Box 7. Long-term sustainability of the RDI infrastructure

According to EIROforum (2015), the following five criteria are key to ensuring the long-term sustainability of RDI infrastructures.

- An infrastructure must be relevant to its scientific community and able to generate scientific excellence. Hence, before establishing a new RDI infrastructure, clearly defining its added value to the scientific community and its complementarity with respect to already existing facilities is regarded as essential.
- The governance model and legal framework should be sustainable. An infrastructure's managers should ensure that adequate programmes/projects are implemented to rapidly respond to the needs and ambitions of all member states/funders and to enable full exploitation of the research results.
- The funding model should be sustainable. The necessary on-going investments needed for optimal operation should be guaranteed to ensure that the infrastructure can continuously carry out its cutting-edge research activities.
- The infrastructure must attract scientific talent and develop a critical mass of scientific expertise. The ability to attract and retain talented researchers, which in turn builds scientific excellence and allows the infrastructure to maintain high standards, is closely related to the potential of the infrastructure to enable cutting-edge science.
- The infrastructure must drive major socio-economic changes and must play a crucial role in the development of society. The expected long-term changes led by a RDI infrastructure may concern two different levels: society as a whole and the immediate local environment.

[29] See www.capital-investment.co.uk

[30] Specifically, the United States, Great Britain, France, Belgium, and the Netherlands.

4. Forecasting and valuing social costs and benefits

Although financial analysis uses observed prices, for economic analysis (used synonymously with socio-economic impact, i.e. welfare analysis), such flows must be converted into shadow prices. In addition, the CBA needs to account for the positive and negative additional effects that are relevant to society but that have not been considered from the financial perspective (i.e. costs or benefits that spill over from the project towards other parties without monetary compensation)[31].

Externalities are particularly relevant for RDI infrastructure projects given the imperfect market in which they operate. By definition, knowledge creation is characterised by the fact that ex-ante information is imperfect because users literally only know that some probabilities are associated with different research outcomes when they embark on studying something unknown. Moreover, knowledge *per se* is an intangible public good and has a number of special features, namely:

- It is *non-rival*: a discovered fact does not prevent anyone else from potentially using the same knowledge; in other words, the benefits derived from knowledge may extend to mankind in general; and,
- To a certain extent, knowledge may be *non-excludable* because some knowledge cannot be patented or otherwise protected; thus, knowledge created by RDI projects is often a public good, which creates a market failure[32].

After illustrating the concept of shadow prices and their use, this section provides a detailed discussion of the social benefits associated with RDI infrastructure projects.

4.1 Shadow prices and main approaches for their estimation

The project's welfare impact is assessed by comparing its costs and benefits expressed as their social opportunity cost, rather than their observed market prices. Markets are typically distorted[33] and, thus, market prices are not signals of the social value of goods and are driven by different economic or political factors (Florio, 2014). Therefore, correcting for these distortions means identifying the marginal social (or shadow) value of goods, i.e. their opportunity cost to society of producing or consuming more or less of any good (see ***Errore. L'origine riferimento non è stata trovata.***).

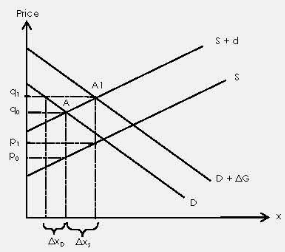
[31] According to standard practice, economic analysis involves three steps. First, financial costs are transformed into accounting prices using suitable conversion factors. Second, direct benefits to users are converted by replacing financial revenues with an estimation of users' WTP for project outputs less changes in supply costs. Third, the monetary valuation of externalities is added (EC, 2014).

[32] In economics, a market failure implies that the quantity of public goods demanded by consumers does not equate the quantity supplied by suppliers. This imbalance creates a case for public intervention.

[33] Distortions refer to taxes, domestic and international constraints on capital and labour flows, monopoly or oligopoly price setting, suboptimal distribution of assets and income, and information asymmetries.

Box 8. Shadow price of experimental equipment

Consider a major RDI project that uses as input x special experimental equipment purchased in the market in which p is the supply price (marginal cost) of the equipment and q = p+d is the demand price before the project, where d is the distortion of the input price, created e.g. by an import duty. The new project is funded by a public sector grant and its effect can be seen as a shock affecting the previous equilibrium. The figure below shows the market for x. The supply curve S exhibits the quantity supplied at various supply prices, and the demand curve D shows the quantity demanded at various demand prices. By adding the distortion d to the original supply curve, a new supply curve S+d is obtained.



Market equilibrium occurs in A, with p_0 being the supply price and q_0 the demand price ($q_0 = p_0+d$). If the new RDI project purchases an amount ΔG from the market, the demand curve shifts right (recall that the new demand is supported by a public sector transfer), causing the demand and supply prices to rise to q_1 and p_1, respectively. Therefore, the project demand of new equipment ΔG is satisfied partially from an increase in supply (Δx_S) and partially from a reduction in demand (Δx_D) by the other users of the equipment because of the higher price. This change in the previous equilibrium caused by the project is associated with an opportunity cost. On the one side, there is an increase of suppliers' costs since they have to produce an additional amount of x_S: this opportunity cost can be approximated by $p_0\Delta x_S$. On the other side there is the reduction of users' benefits due to the foregoing purchases of x_D which can be approximated by $q_0\Delta x_D$. The sum of these two effects gives the shadow price (v) of the equipment x used in the project:

$$v = \frac{p\Delta x_S}{\Delta G} - \frac{q\Delta x_D}{\Delta G}$$

This equation shows that v is different from both p and q, as it is a linear combination of both, as $\frac{\Delta x_D}{\Delta G} < 0$. The same formula holds if the project outputs displace the market supply and induce market demand. Finally, two special cases exist, namely:

- when the demand price is constant (i.e. the demand is infinitely elastic), the shadow price is q = p+*d*; and,
- when the supply price is constant (i.e. the elasticity of supply is infinite), the shadow price is p.

These simple examples ignore general equilibrium effects, i.e. consequences to other markets.

Source: Authors based on Boadway (2006).

Shadow prices can be empirically estimated using several approaches (reviewed *inter alia* by Boardman *et al.*, 2006; Brent, 2006; De Rus, 2010; Florio, 2014; Potts, 2002; and Potts, 2012a). In this section, two main approaches for their estimation are mentioned: users' marginal willingness-to-pay (WTP) and the long-run marginal social cost of production (LRMSC).

- The concept of (marginal) WTP refers to the maximum amount of money that the consumer is willing to pay to have an additional unit of a good[34]. This concept is primary used for the empirical valuation of a project's direct benefits, i.e. those related to the use of the goods or services rendered by the project, and for externalities. However, in some specific cases, WTP can also be used to proxy the opportunity cost of a project's inputs, such as land, whose use in the project leads to an adjustment in the net demand of other consumers of that good. The importance to using WTP is particularly evident for estimating externalities for which no monetary compensation is paid.
- The concept of the LRMSC of a good refers to the increase in the total cost to society as a whole, i.e. private costs plus external costs, required to increase the production of the good by one unit, keeping constant the production levels of all other goods. Typically, the LRMSC measures the economic value of non-tradable inputs, for which an increase in demand results in increased production. However, when the WTP approach is not possible or relevant, the LRMSC can be used to evaluate the output of some projects.

The example in *Box 8* shows that, in some cases, the combination of WTP and LRMSC is a proxy for the shadow price. However, the following sections treat cases in which either one or the other is appropriate, leaving the issue of combined estimation to specific applications.

[34] In a CBA framework, a good stands for a benefit or avoided costs. Hence, the WTP refers to the amount of money people are willing to pay to enjoy a benefit or to avoid a cost (Boadway, 2006).

4.2 Conversion factors for inputs other than labour

A simplified operational approach for expressing the costs of RDI infrastructures in shadow prices consists of applying suitable conversion factors to the main cost items considered in the financial analysis (e.g. materials, land, building construction, electricity) possibly retrieved from already existing benchmarks developed by the national public authorities for CBA in other fields.

A conversion factor is defined as the ratio between shadow prices and market prices. Thus, it represents the factor by which market prices have to be multiplied to obtain the shadow price[35].

Different approaches exist to calculate conversion factors. In general, if inputs are tradable goods, border prices are used[36]. Regarding non-tradable goods (i.e. procured domestically), a different approach is used depending on whether they are minor or major project items. For minor items, the standard conversion factor is adopted[37]. For major items (e.g. land, civil works, machinery, equipment), *ad hoc* assumptions should be made depending on the specific hypotheses adopted for market conditions.

For instance, consider land used for RDI infrastructures. As long as the real estate market operates under competitive conditions and no distortions occur, the financial cost of land can be assumed to be a reasonable proxy for its economic cost. However, in some RDI projects, land is provided free of cost by universities, donors, or public sector entities. Although no financial cost is included as part of the investment cost, corrections are needed to reflect the opportunity cost, which is the net benefit lost from the best possible alternative use of that land.

4.3 Conversion factors for labour

Special attention should be given to the opportunity cost of labour, measured using the shadow wage. The shadow wage rate is the social opportunity cost of labour and may differ from the observed wage because of distortions related to labour (e.g. unemployment, migration, taxes, minimum wages) and in the product markets. Following the opportunity cost concept, the shadow wage should reflect the social benefit of employing a person in a region/country and sector characterised by certain labour market conditions, rather than in others[38].

The application of a shadow wage to the labour cost is particularly important because it is the recommended way to capture a project's effects on employment (European Commission, 2014; Del Bo et al., 2011). Against the conventional argument (primarily referred to by politicians and project managers) that jobs created are a direct benefit of an infrastructure project (with the consequences that salaries of newly employed scientists are sometimes added as such to other economic benefits), the economic reasoning points to the consideration that wages are rather a share of the total costs of the project. Therefore, the social benefit of employment has to be taken into account by exclusively using shadow wages, i.e. by considering that the opportunity cost of employing a person in the project under assessment is lower than that from using the same person for any alternative use (including, possibly, unemployment).

According to the DG Regio Guide (European Commission, 2014), the shadow wage can be assumed:

- equal to or typically not less than the value of unemployment benefits (or other proxies when unemployment benefits do not exist) for unskilled workers previously employed in similar activities (in principle, if unemployment benefits are high, the shadow wage can be lower);
- equal to the value of the output forgone in previous informal activities for unskilled workers drawn to the project from such activities; and,
- equal or close to the market wage for skilled workers previously employed in similar activities.

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[35] If the conversion factor for a good is higher than one, the opportunity cost of that good is higher than that captured by the market. Conversely, if the conversion factor is lower than one, then the observed price is higher than the shadow price. For instance, a conversion factor of 0.9 implies that the shadow price is 10% below the market price or that the market price is 11.1% higher than the shadow price (1/0.9 = 1.111) given taxes or other market distortions that add to the marginal social value of a good and determine a higher market price.

[36] Empirically, FOB (free on board, before insurance and freight charges) prices are retained through the best guess of the economic value of exported outputs, whereas that of imported inputs is captured by CIF (cost, insurance, and freight) prices. This approach relies on Little and Mirrlees (1974).

[37] Following Little and Mirrlees (1974), the standard conversion factor is a proxy of the average distance between world prices and domestic prices. The formula is SCF = (M+X)/(M+X+TM), where M is the total value of imports at shadow prices, i.e. CIF prices; X is the total value of exports at shadow prices, i.e. FOB prices; and TM is the total value of duties on import.

[38] The CBA literature offers different shadow wage formulae on the basis of the different hypothesis on labour and product market conditions. Recent theoretical contributions include Potts (2002); Londero (2003); de Rus (2010); and Potts (2012b). Recent empirical contributions include Honohan (1998); Saleh (2004); Picazo-Tadeo and Reig-Martinez (2005); and Del Bo et al. (2011). The latter presents a new, simple framework for the empirical computation of shadow wages at the regional level and empirical estimations for EU regions.

As a result, the conversion factor should generally be computed for unskilled workers, whereas no conversion factor is normally needed for scientists assuming an international non-distorted labour market in their case. However, when a shortage of a skilled workforce exists in a country, a suitable conversion factor must be computed even for such workers. This anomaly may lead to a conversion factor higher than 1.

In some cases, migrant workers are employed by RDI facilities. The economic cost of their labour should reflect the opportunity cost from the country of origin, not from the country in which the project is located, unless wages are the same in the two countries. When wages are higher in the country in which the infrastructure is located than in the country of origin, the appropriate conversion factor for labour is equal to the sum of the opportunity cost in the country of origin and the migration costs divided by the project wage (Asian Development Bank, 2013).

1. Shadow wages

The appraisal of a greenfield materials science and engineering laboratory of national relevance includes selecting its location among possible alternative sites. Region ALFA is affected by high unemployment of unskilled workers, but not of other labour force. The labour market in Region BETA is under full employment. The laboratory will hire twenty senior researchers; forty-five young researchers; thirty unskilled workers. The real market wage forecasted is EUR 50,000 per year for senior researchers, EUR 30,000 for young researcher, and EUR 24,000 for unskilled workers and is the same in both regions.

The shadow wages have been previously estimated by a national authority in compliance with government CBA guidelines :

- equal to market wage for the forty-five young researchers since their labor market is assumed to be open to international competition, with easy mobility across countries. Hence, the cumulated annual shadow labor cost for young researchers is EUR 1.35 million in both regions;
- 25% higher than market wage for the twenty senior researchers as their reference labour market is not fully competitive since for them the international mobility is hindered by linguistic barriers and high relocation costs. Hence, the cumulate annual shadow labor cost for senior researchers is (EUR 50,000 * 1.25 * 20) = EUR 1.25 million;
- 25% lower than market wage for the thirty unskilled workers due to high unemployment in region ALFA, but equal to market wage in region BETA. Hence, the cumulated annual shadow labor cost for unskilled workers in region ALFA is (EUR 24,000 * 0.75 * 30) = EUR 540,000, while it is 720,000 in region BETA. As a consequence, ceteris paribus, the Net Present Value of the project will be higher by EUR 180,000 in region ALFA.

The laboratory is expected to recur to some local enterprises as suppliers of the infrastructure during the construction phase. These firms will increase the number of unskilled employees in both regions, but only in region ALFA this fact will decrease local unemployment. This additional effect on regional employment is already captured through the adoption of the different shadow wages in the two regions. No additional benefit calculations are needed. Other employment effects are expected as the result of adoption of innovations in materials by a range of industries in the country. However, as the laboratory is of national relevance, such impact is not relevant in the selection of the location.

5. Social benefits

Once the main beneficiaries (either users or non-users) of an RDI infrastructure have been identified (see section 1.4), a list of typical benefits can be attached to each group. Depending on the project's nature, some of them recur for different types of target groups. For instance, the value of patents as a potential benefit may accrue to large businesses, SMEs, academics, or inventors outside academia.

This section reviews the possible approaches to forecasting the quantities of benefits over the project's time horizon and giving them an economic value.

The intensity of each benefit may be highly variable across the different typologies of RDI infrastructures. For instance, the social benefit of human capital formation is highly relevant for basic or applied research infrastructures through which students are often involved in research activities. However, this benefit is less relevant for technological development and innovation infrastructures. Only a case-by-case appraisal can determine the category of benefit that is more or less important for a specific project.

Table 3. Navigator table of typical benefits associated with RDI infrastructure projects

Benefit	Marginal social value	Estimation method	Beneficiary target group(s)	Page
Development of new/improved products, services and technologies	Incremental shadow profits	Survey of business; statistical inference from company data	Businesses	29
Patents	Marginal Social value of patents	Inventors' survey; statistical inference from data on decision to renew patents or on economic terms of patent transactions; stock market valuation of market patent portfolio	Businesses, Academics; Researchers	31
Establishment of more numerous or more long-lived start-ups and spin-offs	Incremental shadow profits	Survey of start-ups and spin-offs; statistical inference from start-ups and spin-offs data; benefit transfer	Start-ups and spin-offs	34
Knowledge spillovers (not protected by patents)	Incremental shadow profits; avoided costs, willingness-to-pay for time saving	Survey of businesses; avoided cost for the production or purchase of a technology; avoided cost thanks to the exploitation of a new technology Benefit transfer	Businesses; Professionals; Citizens; Organisations	36
Learning-by-doing benefits for the supply chain	Incremental shadow profits; avoided costs,	Survey of business; statistical inference from company data; Benefit transfer	RDI suppliers	38
Human capital formation	Incremental lifelong salary	Survey to former students; Benefit transfer	Young professionals, researcher; Students	41
Knowledge outputs and their impact	Marginal production cost	Gross salary of scientists; Value of time	Academics; Researchers	44
Provision of services	Long-run-marginal cost (or observed price) or WTP for the service	Cost incurred by the infrastructure to make the services available; Contingent valuation	Businesses; Professionals; Organisations; Government; Third research teams	48
Social benefits of RDI services for target groups	Avoided costs, Willingness-to-pay	Avoided economic cost of emissions; Opportunity cost of avoided energy sources; Avoided damage of capital stocks; Travel cost Method; Opportunity cost of land; Contingent valuation, Cost of illness; revealed preference approach; human capital approach; Benefit transfer	Businesses; Target groups of population	49
Recreational benefits for the general public	Willingness-to-pay	Travel cost method; Contingent valuation; Choice modelling; Benefit transfer	General public	54
Non-use benefits of new knowledge as a public good	Willingness-to-pay	Contingent valuation; Benefit transfer	Tax-payers	56

5.1 Development of new/improved products, services, and technologies

The development of new/improved products, services, or technologies is the expected direct benefit of innovation infrastructures. These developments may accrue to either the RDI infrastructure itself (e.g. the research centre of a large manufacturing company that directly sells the new products on the market) or external users (e.g. users of a technological park or incubators). In minor cases, they may be side effects of fundamental or applied research infrastructures.

When a project entails the development of innovative products, services, and technologies, the social value of these goods is expressed using the *incremental shadow profits* expected from their sale. In particular: 'incremental' means that profits expected from the sale of new/improved products, services, and technologies generated by the project must be compared with the profits in the without-the-project scenario; and, 'shadow' means that market distortions should be duly considered; for instance, the shadow profit is higher than the gross financial profit if the infrastructure is located in an area of high unemployment.

Given that i is the number of innovations (products, services, and technologies) over time t, $\mathbb{E}(\Pi_{it})$ represents the expected incremental profits directly imputable to these innovations and s_t represents the discount factor. Then, the expected present value of developing new/improved products, services, and technologies (*Z*) is expressed as:

$$\mathbb{E}(Z) = \sum_{i=1}^{I} \sum_{t=0}^{T} s_t \cdot \mathbb{E}(\Pi_{it}).$$

Empirics

The ex-ante estimation of these benefits involves the following calculations.

- The benefits must be quantified by forecasting the demand for new/improved products/services/technologies over time. This forecast depends on the project's objective and, as best as possible, should rely on benchmarking with similar RDI infrastructures and interviews with experts in the considered sector;
- The marginal value of new/improved products/services/technologies should be estimated. However, if the expected profit from the new/improved products/services/technologies has been included among the project's financial revenues (i.e. when the new/improved products/service/technology is directly sold by the infrastructure), the economic estimation of their value should not be included in the economic analysis, provided that a suitable conversion factor is used to convert the financial flows from direct commercial exploitation of innovations.

The following different possible approaches exist to predicting expected profits.

- Information on profitability, average costs, and sales can be retrieved from databases in the public domain or may be granted by data providers. Typically, earnings before interest, taxes, depreciation, and amortisation (EBITDA) can be used to proxy companies' profits because interest and taxes are effectively transfers between agents and depreciation is inconsistent with the discounted cash flow approach that supports the computation of the NPV. For instance, the Amadeus Database, maintained by the consultancy Bureau van Dijk[39], which provides balance sheet data reported to national registries and statistical offices by European companies, has been used by Florio *et al.* (2015) to calculate average sector-specific values for profitability up to the four-digit NACE level.
- Benchmarking with similar RDI infrastructures in other contexts could also offer some inputs to forecasting future profits, and access to systematic project datasets at national or supranational levels may be helpful.
- Interviews with experts in the sector can assist in conjecturing on the possible changes in the profitability of businesses under different scenarios.

For the purpose of exemplification, the ten-year average EBITDA margins associated with companies whose primary activity falls within a selected list of NACE codes[40] are presented in Table 4 and are broken down by country (Italy, France, Germany, and the United Kingdom). Data were gathered from the ORBIS world database of companies' financial information[41] and refer to sectors often involved in the procurement of major RDI infrastructures.

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[39] The database is available at www.bvdinfo.com/en-gb/home.

[40] Manufacture of basic metals (24), manufacture of computer, electronic, and optical products (26), manufacture of electrical equipment (27), manufacture of machinery and equipment n.e.c. (28), telecommunications (61), computer programming, consultancy, and related activities (62).

[41] The ORBIS database is maintained by the consultancy Bureau van Dijk.

Table 4. Ten-year (2004–2013) average of companies' median EBITDA margin (%) by sector and country

Industry (NACE sector)	NACE Code	Italy	France	Germany	United Kingdom
Manufacture of basic metals	24	7.6	15.3	7.1	35.0
Manuf. of computer, electronic and optical products	26	11.2	8.3	11.7	14.4
Manuf. of electrical equipment	27	10.3	16.4	11.7	11.2
Manuf. of machinery and equipment n.e.c.	28	13.1	10.3	9.8	17.6
Telecommunications	61	40.1	13.8	11.3	10.0
Computer programming, consultancy and related activities	62	11.3	15.3	8.0	8.3

Source: Authors' elaborations based on ORBIS database

2. Shadow profits of high tech firms

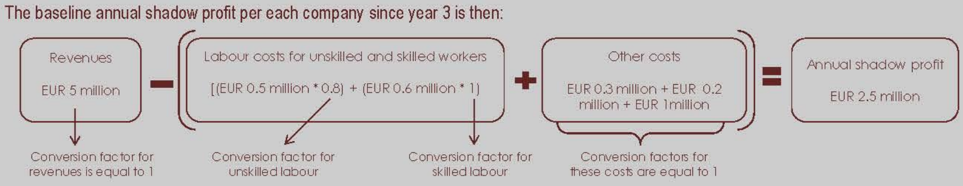
A technology park in country GAMMA is expected to support 45 new enterprises in the red biotechnology field. These enterprises will benefit from the use of testing and prototyping shared laboratories of the infrastructure. These activities will eventually lead to the development of new marketable products. The time horizon of the project is 15 years. According to sector analyses available, the red biotech sector has the following features:

- young, small-cap biotech companies may have low or negative earnings for extended periods because they face high R&D costs throughout the lengthy process of bringing their first product to market;
- the expected annual shadow profit is highly variable. Indeed, some biotech enterprises have no hopes of ever making money, while others which have products already established in the marketplace are quite profitable.

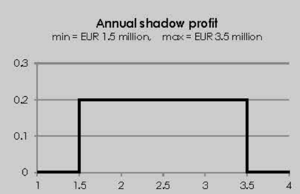
The baseline forecast is that:

- the yearly average amount of revenues per company is zero for the first two years and then real EUR 5 million;
- the yearly salaries for unskilled workers amount to EUR 0.5 million, while those for skilled workers amount to 0.6 million;
- the conversion factor for unskilled labour is estimated at 0.8 due to unemployment in the region, while that for skilled labour is estimated equal to 1;
- the yearly average cost of rents and utilities is EUR 0.3 million and EUR 0.2 million, respectively;
- the yearly average production cost is EUR 1 million;
- the conversion factors for rents, utilities and production costs is assumed equal to one.

The baseline annual shadow profit per each company since year 3 is then:



Given the high uncertainty about the shadow profit, the project promoter (based on previous cases) assumes that the shadow profit may take any value between EUR 1.5 million and EUR 3.5 million per year. Thus, a rectangular distribution is hypothesised. This distribution will feed in to the Montecarlo simulation of the ENPV.



5.2 Patents

When a patent is registered, it produces a private return to the inventor and potential knowledge spillover to society. Indeed, a public document is issued containing information on various aspects of the invention, including citations to existing patents. When approved this document grants the inventor an exclusive right for the commercial use of the patented invention for a predetermined period and serves to delimit the scope of the property right granted to the patent owner. Thus, the cited patents represent the previously existing knowledge on which the citing patent builds, and over which the citing patent cannot have a claim (Jaffe, Trajtenberg, and Henderson, 1993; Deng, 2005).

The fact that patent citations reveal 'prior art' that an inventor has learned makes them potential measures of the knowledge spillovers from past inventions to the current invention. In other words, citations of a patent by many subsequent patents suggest that the patent generated significant technological spillovers because numerous developments build on the knowledge that it embodies. Thus, patent citations have become a broadly used proxy for estimating the social value of patented technologies (see, for instance, Trajtenberg et al., 1997; Caballero and Jaffe, 1993; and Jaffe and Trajtenberg, 1999).

In a CBA framework, both the private returns and the knowledge spillovers brought about by patents granted by a RDI infrastructure represent a benefit that should be considered. Therefore, the *marginal social value of the patent generated by a RDI infrastructure* should be forecasted, provided that double counting from the change in the expected profit from the sale of innovative products is avoided (i.e. when they are appropriated directly by the RDI). Given i as the number of patents over time t, $v_{(pvit,exit)}$ as the patent marginal social value, and s_t as the discount factor, the expected present value of this benefit is expressed as:

$$\mathbb{E}(P) = \sum_{i=1}^{I} \sum_{t=0}^{T} s_t \cdot \mathbb{E}(MSV_{(pvit,exit)}),$$

where the marginal social value (MSV)includes both the private value (pv_{it}) and the externality (ex_{it}), i.e. the knowledge spillover brought about by patents granted by a RDI infrastructure.

Empirics

The ex-ante estimation of this benefit involves the following activities.

- The number of patents that will be registered by the RDI project over time is forecasted. This activity involves either using a promoter's track record on patenting or referring to observational data related to similar infrastructures, if available. Alternatively, considering shortcuts may be useful, including the correlation between the existing statistics on the number of patents granted and the number of R&D personnel in a given area/industry/domain.
- The average rate of usage of granted patents (use) is forecasted. This activity involves, again, either using a promoter's history on patenting or referring to observational data related to citations of patents issued in the same scientific field or in similar infrastructures, if available. The average rate of patent usage, proxied by the median number of lifetime forward citations[42] per patent, is important to understanding the actual rate of exploitation and, in turn, the knowledge spillovers resulting from patents granted by a RDI infrastructure.
- The average number of references (ref), i.e. backward citations[43] to existing patents, is forecasted, which is typically included in patents issued in the relevant technological field.
- The marginal private value of patents is estimated, and double counting given the change in expected profits from the sale of innovations (if they are directly appropriated by the RI) is carefully avoided. In fact, depending on the estimating method used, the value of a patent may or may not already include the market value of the patented invention. In principle, the patent value should be based on the discounted sum of the yearly profits that the patent holder expects to earn because of the patent, net of the equivalent discount stream of profits without the patent (European Commission, 2006).
- The externality of patents in monetary terms is estimated. As mentioned, patent citations mirror the technological importance of a patent for the development of subsequent technologies (Squicciarini *et al.*, 2013). In other words, a citation is a measure of the knowledge spillovers from past inventions to the current invention. However, simply counting

[42] To understand the relationship between 'backward citation' (i.e. patents cited by a new patent) and 'forward citation' (i.e. number of times a patent has subsequently been cited), consider the following example. If Patent A (2005) is cited by Patent B (2015) then Patent A is a backward citation of Patent B, whereas Patent B is a forward citation of Patent A. Most search databases allow both backward and forward citation searching.

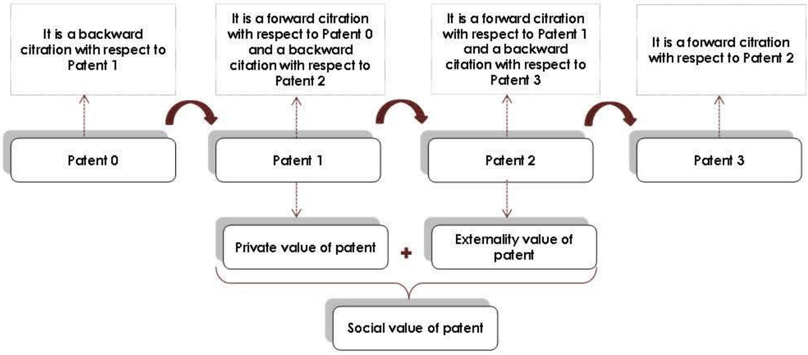
[43] Ibid.

citations does not provide information on a patent's value in monetary terms. To attach a monetary value to the stream of citations produced by a patent, the following formula can be used:

$$\mathbb{E}(ex_{it}) = \sum_{i=1}^{I} \sum_{t=0}^{T} use * \frac{\mathbb{E}(pv_{it})}{ref},$$

where use is the average rate of usage of granted patents, ref is the average number of references included in patents issued in the relevant technological field, and pv_{it} is the private value of patents granted in the relevant technological field.

Figure 2. The social value of patents



Source: Authors

A range of possible information and statistics (including patents and citations counts) useful for forecasting the number of project patents can be retrieved from several repositories[44]. However, importantly, note that only patents granted by patent offices generate both a private value and knowledge spillover. Instead, patent applications or 'invention disclosures' which are not granted have a private value of zero, while their externalities could be positive. When patents granted statistics are not available, an assumption is made about the number of patents that eventually are registered.

Concerning the estimation of the private value of patents, different empirical approaches can be discussed (see

Measurement of patent private value: overview of different approaches).

Box 9. Measurement of patent private value: overview of different approaches

The concept of private value takes into account only the value added of the patent for its holder. Thus, private value can be defined as the depreciated sum of the expected cash flows of the owning entity from the patent. The following three main lines of work have been followed by researchers to estimate or infer the private economic value of patents.

- Estimates based on a patent-holder's behaviour include methods that analyse either the decisions to renew (or not) patents and pay the related fees (see Pakes, 1986; Schankerman and Pakes, 1986; Schankerman, 1998; Lanjouw, 1998; and Bessen, 2006) or the economic terms of actual patent transactions (see Serrano, 2008; Sneed and Johnson, 2009; Leone and Oriani, 2008; and Sakakibara, 2010).
- Estimates based on inventors' surveys involve directly asking the inventor to provide an estimate of the value of his/her patents on the basis of the price at which he/she would be willing to sell the patent (see Harhoff et al., 1999; Harhoff et al., 2003a; Harhoff et al., 2003b; and Gambardella et al., 2008).
- Estimates based on external investors' valuations include methods either based on stock market valuations of patent portfolios of publicly listed companies (see Griliches, 1981; Cockburn and Griliches, 1988; Hall et al., 2005; and Hall et al., 2007) or valuations made by venture capital firms of intellectual property-based start-up companies (see Lerner, 1994 and Hsu and Ziedonis; 2008).

At the European level, a reference study was published by the European Commission in 2006[45]. The analysis relies on a questionnaire survey of almost 10,000 inventors in eight European countries[46]. Patents belonging to different technology classes were considered. To obtain a measure of patent value, inventors were asked to provide their best estimate of the value of their

[44] For instance, the EPO Worldwide Patent Statistical Database – also known as EPO PATSTAT – the Eurostat statistics available under the 'Science & Technology' statistics; the Trilateral co-operation website, which provides statistics from the EPO, JPO, and USPTO dating back to 1996 in the annual Trilateral Statistical Reports; the reports provide an overview of worldwide patenting activities. The WIPO website provides patent and Patent Cooperation Treaty statistics; the OECD's patent indicators reflect trends in innovative activity across a broad range of OECD and non-OECD countries, with six main sections: EPO, USPTO, and JPO patent families; patenting at the national, regional, and international level; patenting in selected technology areas; patents by institutional sector; international co-operation in patenting; and European and international patent citations.

[45] See European Commission (2006).

[46] The considered countries are Denmark, France, Germany, Hungary, Italy, the Netherlands, Spain, and the United Kingdom

patents on the basis of the price at which he/she would be willing to sell his/her patent. This study found that the value of European patents is typically between EUR 100,000 and EUR 300,000, with a small share of patents yielding economic returns higher than EUR 3 million and an even smaller share valued at more than EUR 10 million. Thus, on average a patent in the considered EU-8 countries is worth approximately EUR 3 million. However, because the distribution of patent values is very skewed, the median patent is worth EUR 300,000.

Table 5. Average patent values by country and technological area

Country	Average patent value (EUR thousands)	Median patent value (EUR thousands)	Technological area	Average patent value (EUR thousands)	Median patent value (EUR thousands)
Denmark	2,947	300	Pharmaceuticals, cosmetics	5,260	605
Germany	2,958	305	Macromolecular chemistry, polymers	3,980	449
Spain	3,029	307	Space technology weapons	3,854	414
France	2,922	293	Environmental technology	3,250	354
Hungary	3,647	408	Biotechnology	3,134	336
Italy	3,007	297	Semiconductor	2,555	284
The Netherland	2,788	285	Telecommunications	2,331	247
United Kingdom	3,355	332	Electrical devices, engineering, energy	1,938	211

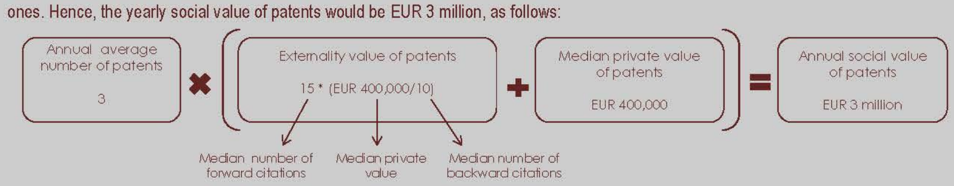
Source: European Commission (2006).

Because patent values are acknowledged to vary significantly across sectors, technological fields, and geographic areas, considering country/region, sector, and technology-specific statistics when available is useful.

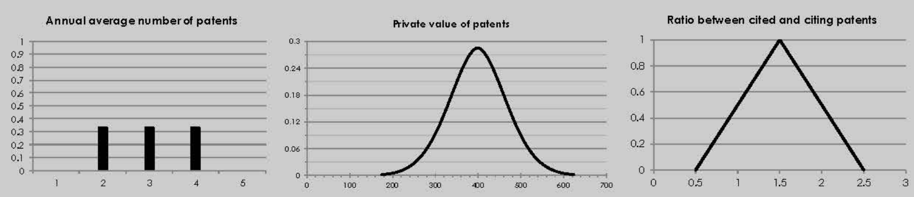
3. Estimating the social value of patents

Region DELTA is a hub of specialty and fine chemicals industry. According to regional statistics, one European patent for every 50 researchers was granted every year in the past decade. A consortium of two universities and of five companies has started a feasibility study for a new research infrastructure in molecular chemistry. The infrastructure is envisaged to employ 150 researchers for the entire time horizon. The baseline forecast of the annual average number of patents expected is 3, conservatively based on the past track record in the region.

According to data retrieved from a meta-analysis carried out by the academics of the two universities, the median market value of patents in the field of molecular chemistry is EUR 400,000. Moreover, according to statistics on patent citations retrieved from databases maintained by similar facilities, the median number of backward and forward citations in the molecular chemistry filed is respectively 10 and 15. Assuming that the externalities are linear in the number of citations, the new patent benefits from ten previous discoveries, and will benefit fifteen future ones. Hence, the yearly social value of patents would be EUR 3 million, as follows:



Since the number and the value of patents are highly uncertain ex-ante, probability distributions are considered instead of punctual values. The annual number of patents according to interviewed experts can have a discrete probability distribution taking value of 2,3 or 4, while the value of a patent can have a normal distribution with mean EUR 400,000 and standard deviation of EUR 150,000[47]. Also the ratio between cited and citing patents is uncertain, and a triangular distribution (minimum value = 0.5; modal value = 1.5; and maximum value = 2.5) is assumed. Using a Monte Carlo simulation technique these distribution assumptions can be combined and the conditional expected total benefit of patents estimated.



5.3 Start-ups and spin-offs

The establishment of start-ups and spin-offs can be one of the intended objectives of innovation infrastructures, as it is for incubator centres. However, this establishment can also be a side effect of fundamental and applied research infrastructures, such as university laboratories. Whatever their origin, the objective of start-ups and spin-offs is ultimately to develop and commercialise new products, services, and technologies.

The benefits produced by a RDI infrastructure to start-ups and spin-offs can be related to either the establishment of new firms or (and) an increase in the survival rate. If the RDI infrastructure contributes to the establishment of start-ups and spin-offs, the economic value of this benefit is valued as the *expected shadow profit* gained by the created business during its overall expected lifetime compared with the without-the-project scenario. Whereas the equity return to investors (e.g. business incubator) and the operating revenues from the sale of consultancy services leading to the establishment of, for example, start-ups, are considered among inflows in the financial analysis, they do not enter in the economic analysis to avoid double counting the considered benefit.

When the RDI infrastructure contributes to increasing the survival rate of start-ups, then the benefit is valued as the incremental expected shadow profit attained by businesses that survive longer than in the without-the-project scenario.

Empirics

The ex-ante estimation of this benefit involves:

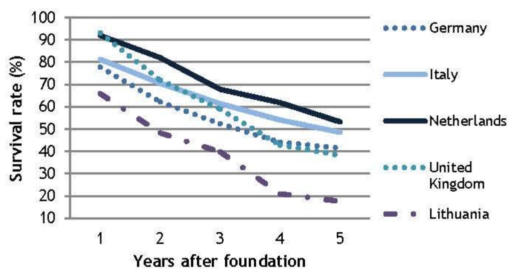
- Forecasting the *number* of start-ups and/or spin-offs expected to be created by the infrastructure during the entire reference period;

[47] It is worth noting that, in general, we suggest to relay on median values instead of average ones when choosing the baseline values in the deterministic model. However, in a probabilistic model, probability distributions should be considered instead of punctual value. Therefore, a probability distribution (characterized by its typical parameters, e.g. mean and standard deviation for normal distribution) should be guessed around this median value.

- Establishing the *expected lifetime and survival rate* of start-ups and spin-offs (when the infrastructure contributes to increasing the life expectancy of start-ups, the expected increase in their survival rate must be estimated); and,
- Estimating the expected *profit* generated by start-up and spin-offs created by the RDI infrastructure.

The median number of start-ups and/or spin-offs created by RDI infrastructures in specific countries and sectors, and their expected lifetimes and survival rates, can be proxied by looking at similar infrastructures in other contexts or retrieved from official statistical database or the literature.[48]

Figure 3. Example of average survival rates in different countries for all sectors of industry, construction, and services except insurance activities of holding companies (*).



(*)codes: B-S_X_K642) retrieved from Eurostat business demography statistics (2012)

Table 6. Example of survival rates of university spin-offs in various countries and two universities

Country	Survival rate	Years	Source
Netherlands	83%	9	Shane, 2004
France	84%	4	Mustar, 1997
Sweden	87%	34	Shane, 2004
N. Ireland	94%	12	Shane, 2004
UK – Oxford	81%	9	Lawton Smith and Ho, 2006
ETH – Zurich	88%	10	Oskarsson and Schläpfer, 2008

Source: Authors adapted from Oskarsson and Schläpfer (2008)

Concerning the expected profit, the considerations presented in section 4.1 remain valid.

[48] Some possible sources of information include Eurostat business demography statistics (2012); Innovation Union Competitiveness report (2011 and 2013); and the European investment Bank (2013).

4. The social value of start-ups supported by an incubator

A specialised incubation park in the electronics engineering industry is aimed at supporting the creation of high-tech start-ups. The project time horizon is 15 years, under a regional development policy instrument. According to the initial feasibility study:

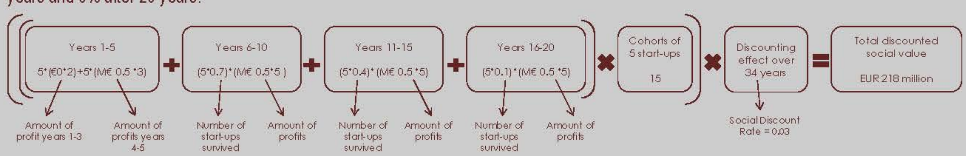
- the park is expected to support on average 5 new enterprises per year and on average each firm remains in the park 3 years, meaning:

Year	1	2	3	4	5	...	14	15
umulate number of start ups	5	10	15	15	15	...	15	15

- based on statistics in similar contexts, the average survival rate is 70% after 5 years, 40% after 10 years, 10% after 15 years and 0% after 20 years in both the with- and without-the project scenarios;
- the average shadow profit of the assisted firms for the first three years will be zero; it then increases to EUR 0.5 million per year;

Hence, the curve of the cumulated profit takes the following form.

In a deterministic model, the total discounted social benefit is the sum of the shadow profits gained by all the enterprises created thanks to the incubation park during the firms overall expected lifetime provided that the survival rate is 70% after 5 years, 40% after 10 years, 10% after 15 years and 0% after 20 years.



5.4 Knowledge spillovers

The RDI infrastructure can produce knowledge spillovers[49] to third parties (businesses, citizens, professionals, public organisations). For instance, open access and open data practices empower everyone to access and re-use, free of charge, results and data from publicly funded research. When the RDI infrastructure produces new knowledge or develops new technologies or products and releases them for free (or at a very low nominal price) and without any form of intellectual property protection, the benefit gained by third parties can be valued using alternative approaches (or a combination of them provided that double counting is carefully avoided) depending on the category of beneficiaries.

- Users are likely to accumulate *incremental shadow profit* from exploiting the knowledge or employing the technology. Given i as the number of entities benefitting from knowledge spillovers over time t, $\mathbb{E}(\Pi_{it})$ as their expected incremental profits directly imputable to the spillover effect, and s_t as the discount factor, the expected present value of technological externalities $\mathbb{E}(F)$ is expressed as:

$$\mathbb{E}(F) = \sum_{i=1}^{I} \sum_{t=0}^{T} s_t \cdot \mathbb{E}(\Pi_{it}).$$

- Users avoid certain *costs* given the exploitation/application of the new knowledge/technology made available for free by the RDI infrastructure. Indeed, in some cases, estimating the costs that no longer need to be sustained for doing something instead of the incremental shadow profit could be more practical. For instance, an innovative combustion technology developed by a research infrastructure offering open access to its research results is considered. The in-

[49] For a theoretical discussion on knowledge spillover, see Mansfield et al. (1977); Griliches (1979); and Hall et al. (2009).

novation can be exploited by businesses to improve their own production processes, thereby significantly reducing their energy costs. These avoided costs represent the value of knowledge spillover for businesses.

- Users *avoid production costs (or the market cost)* given the transferred knowledge made available by the RDI infrastructure. This phenomenon refers to the costs that no longer need to be sustained to produce the knowledge that has been made available for free (or at a very low price) by the RDI infrastructure (or to purchase the same knowledge on the market). For instance, consider new numerical simulation software developed within a research infrastructure and made available free of charge to other research institutes. These institutes can freely use the software instead of producing it or purchasing it (or similar software) on the market, thereby creating cost savings.
- A group of beneficiaries, such as citizens or professionals, are likely to benefit from the *willingness-to-pay for time saving* given that the technologies or products are released for free[50]. As an example of this case is free online software that makes a type of data storage or transmission for professionals easier and more powerful.

Empirics

One way to forecast the possible size of knowledge spillovers of the RDI infrastructure under assessment is to take an already existing similar facility as a benchmark and rely, as far as possible, on the opinion and expectations of experts of the similarity or dissimilarity of technological patterns.

More specifically, depending on the approach followed, the ex-ante estimation of this benefit involves different forecasts. If the incremental shadow profit approach is chosen, the methodology presented in the previous sections applies here as well. Conversely, if the avoided costs approach is preferred, the ex-ante estimation of this benefit requires:

- Forecasting the number of potential beneficiaries affected by the new knowledge or the new/improved technology over time. It should be acknowledged that sometimes innovative products and services are produced for existing but unsatisfied demand (latent demand). In other cases, only potential demand exists. Clearly, the potential demand for a good which does not yet exist should rely on appropriate forecasting methods which may consider among others the potential target users, existing less innovative substitute products or services, similar experiences;
- Estimating the overall cost associated with the production/development of the knowledge/technology and (if relevant) the overall costs avoided given the exploitation/application of the new technology made available for free by the RDI infrastructure (provided that the incremental shadow profit for the same benefit has not been already included). Innovative products (by definition) have no existing market price, however, in some cases it may be possible to determine likely prices by looking at the price of competing, although less innovative, products.

Finally, if the willingness-to-pay approach is considered more suitable, the ex-ante estimation of the benefit requires:

- Forecasting the time saving from the new new/improved technology/products; and,
- Estimating the economic value of time saved; a large body of literature exists on this point.

[50] For time savings, see Hensher (1997); Bates and Whelan (2001); Hensher and Goodwin (2004); Antoniou and Matsoukis (2007); and London Economics, (2013).

5. Benefits from knowledge spillover to third-parties

After three years since its opening, a university research centre in life sciences (taking 3 years to be constructed) is expected to develop a big data multivariate analysis software called ETA as part of a broader scientific program. The centre will be funded by a government grant provided that the software will be released open source. The potential beneficiaries in the scientific domain are around 10,000 scientists but there are also other 10,000 professional users, most of which private companies in different industries. The socio-economic benefit associated to this software is estimated as the avoided cost for the purchase of an equivalent commercial software. Among the software available on the market, there are "Tool 1", available at an annual licence of EUR 11,000 per computer, and "Tool 2", available at EUR 5,000 per individual and commercial users, but needing adaptation costing 4,000. It is expected that each software is going to become obsolete in 5 years. The discounted total benefit is then:

We assume that the displacement effect for the private sector business is negligible (otherwise it should be considered the net effect of positive and negative externalities of the open source release).

Another software ZETA will be developed by the research centre at a total cost of EUR 20 million (calculated as cumulated and discounted time of researchers) after 6 years since its opening. ZETA will be made freely available to the reference scientific community. However, unlike the previous tool, no equivalent commercial software is or will be available on the market. In this case, the benefit associated to the software can be estimated as the avoided cost for all user-entities for developing a new software, equivalent to that made available for free. Based on a benchmarking exercise, the number of institutes, agencies and companies willing to use the software (and with the capacity to develop a similar one in the counterfactual scenario) is 30. The discounted total benefit is then:

Given the uncertainty associated to forecast, distribution probabilities need to be assigned to each variable. In particular:

- For software ETA, the average annual avoided cost per users for the purchase of an equivalent commercial software is estimated by experts having a triangular probability with mode equal to EUR 2,000 per year, lower bound of EUR 1,000 and upper bound of EUR 3,000.
- For software ZETA the variable 'number of user-entities interested in using the free software' is hypothesised having a uniform probability ranging between a minimum of 50 and a maximum of 120.

5.5 Learning-by-doing benefits for the supply chain

High-tech suppliers involved in the design, construction, or operation of infrastructures at the forefront of science or technology can enjoy spillovers from working with/for the RDI infrastructure[51]. Indeed, the firms involved in the supply chain of a RDI infrastructure typically face the challenge of providing non-off-the-shelf industrial solutions to a number of complex technological questions. On the one hand, this situation gives firms the opportunity to collaborate with the scientific and technical staff of the infrastructure and, in turn, to acquire new knowledge and technological skills. On the other hand, the suppliers are incentivised to expand beyond their current state of knowledge. The learning-by-doing benefit of suppliers can yield to different types of developments, ranging from improvements to already existing equipment or manufacturing processes to the invention of new tools that may find applications in other areas of science, services, or industry.

The first attempts to estimate the economic benefit to firms producing equipment for a RDI infrastructure were probably made by the European Organisation for Nuclear Research (CERN)[52]. However, these studies, which typically focus on estimating quantitatively the average 'economic utility'[53] to supplier firms, implicitly assume that the value of learning-by-doing is increased sales

[51] To explore the social returns to R&D, see Bernstein and Nadiri (1991); David et al. (1992); Hertzfeld (1998); and Hall (2009).

[52] See Schmied (1975); Schmied (1982); and Bianchi-Streit et al. (1984). Also in the seventies, first attempts to measure the benefits from the NASA R&D programs were performed (e.g. Midwest Research Institute, 1971). However, these studies usually estimated the productivity changes in the national economy and were not based on production function or cost benefit approaches.

[53] Economic utility was defined as the sum of the increased turnover and cost savings arising directly from the contract, but excluding the value of the contract itself.

and decreased costs. In a CBA framework, the net benefits should be considered and, for this reason, revenues must be considered net of production costs (i.e. profits) and from an incremental perspective.

The social value of learning-by-doing should be evaluated through the *incremental shadow profit* expected by supplier companies[54]. In principle, this increase in profits should be assessed against a counterfactual group of companies operating in the same sector and sharing other characteristics with the companies that actually worked for the infrastructure. A practical way to value ex ante the incremental increase in profits consists of using a 'benefit transfer' approach[55], exploiting the results of an ex post survey of companies within and outside the supply chain of similar infrastructures. Alternatively, the benefit can be valued as the *cost avoided* given the application of the new knowledge and experience obtained for free as a spillover of the procurement contract (for this concept, refer to the previous section).

Empirics

Following the incremental shadow profit approach, the ex-ante estimation of the benefit involves the activities described below.

- The volume of procurement contracts that is likely to generate technological externalities are forecasted. Learning benefits are expected to occur when the procurement contract is for the provision of products that satisfy new technical requirements, usually customised for the infrastructure purpose. Therefore, orders regarding off-the-catalogue products, i.e. items produced for the market and that do not need substantial adaptation for being used, do not entail any spillover effect to suppliers. From an ex ante point of view, determining the technological opportunities opened up by working for the RDI for further profitable investments is a difficult endeavour. Indeed, the potential exploitation opportunities deriving from the development of a new technology might not be evident at the beginning; therefore, immediately identifying all of the technological externalities that might appear in the next years or decades is reasonably impossible. To avoid risking optimism bias, forecasting the possible size of the learning-by-doing benefit by relying, as much as possible, on already existing similar RDI infrastructures as a benchmark and on the opinion and expectations of independent experts is helpful.
- A sales multiplier is estimated to elaborate on the procurement likely to generate learning-by-doing benefits as increased turnover (or decreased costs). For instance, using a multiplier of 3 (as suggested in Bianchi-Streit et al., 1984) indicates that, for every Euro in a procurement contract, a supplier company receive 3 Euros in the form of increased turnover or cost savings. The following table presents the results of different studies aimed at estimating the 'economic utility' ratio in the field of RDI.

Table 7. Economic utility' ratios in the literature

Average values	Organisation	Method	Source
3	CERN	Survey of firms	Schmied (1975);
1.2	CERN	Survey	Schmied (1982);
3	CERN	Survey	Bianchi-Streit et al. (1984)
3	ESA	Survey of firms	Brendle et al. (1980) and Bach et al. (1988)
1.5-1.6	ESA	Survey	Schmied (1982);
4.5	ESA	Survey	Danish Agency for Science (2008)
2.1	NASA Space Programmes	Input-Output model	Bezdek and Wendling (1992)
2-2.7	INFN	Input-Output model	Salina (2006)
3.03	John Innes Centre	Input-Output model	DTZ (2009)

Source: authors based on cited sources.

[54] According to Florio (2014), we maintain that the change in sales does not need to be considered, but instead the change in *net* output (i.e. profit) at shadow prices.

[55] The benefit transfer approach refers to the process of extrapolating the results of existing primary studies (i.e. surveys or other ad-hoc analyses) and transferring them to different populations and contexts. In other words, when a parameter has been previously estimated for a similar project in a different context (e.g. different country, different region), it can be used in another analysis after proper adjustment to take into account technical, socio-economic, geographic, and temporal specificities of the project under evaluation. On the benefit transfer method, see for instance Pearce et al. (2006), the Asian Development Bank (2013), and Florio (2014).

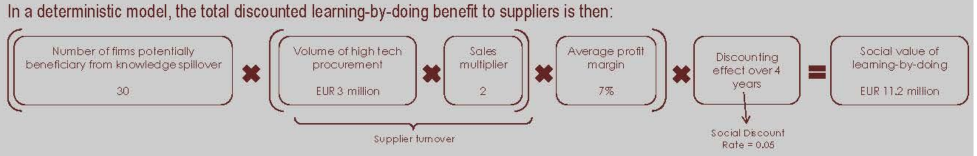
- A profitability measure (e.g. the EBITDA margin) is estimated to multiply the turnover previously calculated. This step is key because it allows for the consideration of increased profits rather than simply increased sales or decreased costs as a benefit for supplier firms.

6. Social value of learning-by-doing

Thirty supplier firms are involved in the provision of customised high-tech items for the construction of a research space satellite for an inter-governmental body. These firms are potentially beneficiaries of technological and knowledge spillovers because the items will be co-designed with the client. Based on forecasted production cost and according to a benchmark analysis to similar infrastructure elsewhere, the following hypotheses holds:

- each firm will be involved in the procurement for 1 year and, on average, the co-design of high-tech items will take 500 working hours. Specifically, the breakdown of suppliers' involvement over the construction period (lasting 4 years) is: five firms in the first year, ten firms respectively the second and the third years, and five firms in the fourth year.
- each firm's volume of procurement potentially associated with learning-by-doing benefit has a uniform probability distribution ranging from EUR 2 million to EUR 4 million (the baseline value is EUR 3 million);
- the sales multiplier has a uniform probability distribution ranging from 1 to 3 (the baseline value is 2);
- the incremental expected profit registered on average by the supplier firms can be approximated by a triangular probability distribution ranging from 1% to 10% with a modal value of 7%. This PDF is the result of a profitability forecasting analysis of suppliers' sub-sectors (spacecraft component; propulsion; lander, rover and probe; micro and nanospacecraft applications) based on data of the last ten years, future market trends and interviews to companies' managers.

In a deterministic model, the total discounted learning-by-doing benefit to suppliers is then:



In a probabilistic model, the computation of the benefit's expected present value requires a Monte Carlo simulation conditional to the probability distribution functions of critical variables such as the profit margin and the sales multiplier.

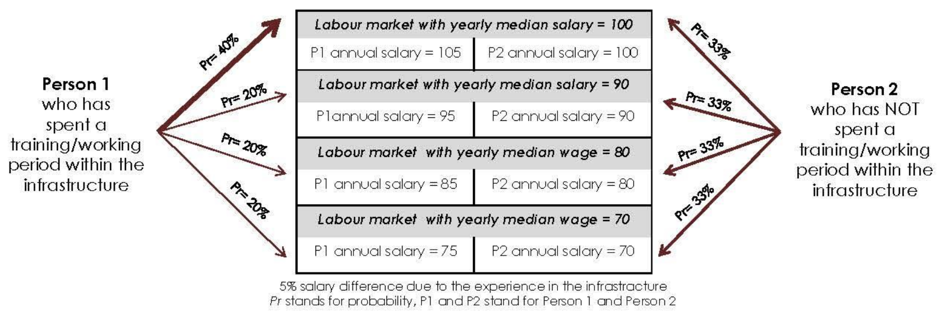
5.6 Human capital formation

Typically, an RDI infrastructure employs four broad groups of staff: a) scientific personnel, b) technical personnel (technicians and engineers), c) administrative and support personnel, and d) PhD students, postdoctoral researchers, and visiting young academics and other short-term users.

For students, postdoctoral researchers, and visiting young scientists who enjoy the possibility of spending time working within a major RDI infrastructure, the main expected benefit is a 'premium' on their future salaries. This premium results from the acquisition of human capital, i.e. new capacity and skills, from experience with the project[56].

The mentioned 'premium' is the *incremental lifelong salary* earned by students and young scientists over their entire careers compared with the without-the-project scenario. Conceptually, two slightly different effects contribute to the formation of this 'premium' salary. On the one hand, the premium reflects the marginal salary increase gained by a former student who spent time at the RDI project relative to the salary that would have been earned anyway, i.e. without the experience offered by the infrastructure. On the other hand, the increase is the result of the fact that people having spent a training period at the infrastructure tend to increase their chances of being hired in labour markets that offer higher average wages.

Figure 4. Example of effects determining the salary premium



Note: Pr = probability, P1 = Person 1, P2 = Person 2. Source: Authors

The expected present value of human capital accumulation benefits, $\mathbb{E}(H)$, can be defined as the sum of the expected increasing earnings, $\mathbb{E}(E_{it})$, gained by RDI students and young scientists and commonly indexed by i, from the moment (at time φ) they leave the RDI infrastructure.

$$\mathbb{E}(H) = \sum_{i=1}^{I} \sum_{t=\varphi}^{T} s_t \cdot \mathbb{E}(E_{it}).$$

Empirics

In principle, assessing the effect produced by the RDI infrastructure on students and young scientists requires a quasi-experiment perspective. Such a perspective implies tracking the careers of cohorts of students in the long run and matching data on the careers of young people with experience in the RDI infrastructure with those who lack such experience. Alternatively, the effect could be estimated using an econometric model, e.g. based on Mincer's human capital earnings function (1974)[57].

[56] Similarly, some capacities and skills can also be acquired by scientists, engineers, and technical staff working at the RDI infrastructure. Once they leave the facility, the increase in earnings they receive compared with what they would have received without their experience at the RDI infrastructure is a 'premium' similar to that enjoyed by young researchers. The evaluation approach presented for young scientists holds for former employees as well.

[57] Jacob Mincer (1974) was the first to derive an empirical formulation of earnings over the lifecycle. In the 1974 formulation, Mincer modelled the natural logarithm of earnings as a function of years of schooling and years of labour market experience. The most broadly used version of Mincer's human capital earnings function is: $\log y = \log y_0 + rS + \beta_1 X + \beta_2 X^2$, where y is earnings, y_0 is the level of earnings of an individual with no education and no experience, S is years of schooling, and X is the years of potential labour market experience.

Box 10. The marginal return to human capital

The estimation of the return to human capital, for both the individual (or private return) and society as a whole, has been the focus of considerable debate in the economics literature. In particular, the private return is defined as the extra salary earned as a result of an increase in human capital, typically proxied by years of schooling. The benchmark model for an empirical estimation of the returns to education is the relationship derived by Mincer (1974), which includes on-the-job training and experience beyond schooling. However, the literature on the impact of education on earnings reveals a broad range of empirical approaches (one factor vs multiple factors model; homogeneous vs heterogeneous returns model; OLS regression; the instrumental variable method; the control function method; the method of matching; and the discount method) that have been adopted to estimate the return and an equally broad range of estimates (see Psacharopoulos, 1994; Psacharopoulos and Patrinos, 2004; Psacharopoulos, 1995; and Heckman et al., 2005 for a review).

As an example, Table 8 presents the results of a small sample of empirical studies, which have attempted to yield comparable results by using cross-country data sources.

Table 8. Average return to education

Country	Harmon et al. (2003) Returns to education, 1995[58]	Blöndal et al. (2002) Private internal rates of return to tertiary education, 1999-2000[59]	Boarini and Strauss (2007) Private internal rates of return to tertiary education, 2001[60]
Austria	6.8	-	6.4
Denmark	5.6	11.3	9.1
Finland	8.7	-	7.8
France	7.8	14.8	9.0
Germany	8.8	8.7	6.3
Ireland	11.3	-	13.1
Italy	6.9	6.5	5.1
Netherland	5.7	12.3	6.2
Portugal	9.7	-	12.2
Spain	7.8	-	5.7
UK	10.4	16.1	12.0

Source: Authors adapted from different sources.

However, from an ex-ante perspective, the estimation of a future premium on salary may require benefit transfer approaches from other contexts, interviews, and expert opinions by specialists such as recruiters in the labour market of interest. Moreover, the marginal increase in earnings ascribable to the RDI infrastructure needs to be carefully tested in the risk analysis.

A benchmark with a similar infrastructure is also needed to forecast the number of students and young scientists spending time within the infrastructure and then entering different labour markets. According to the RAMIRI online handbook[61], the personnel needed during the design, construction, operation, and – finally – decommissioning or upgrade/reorientation of an RDI infrastructure have a very different composition of skills, attitudes, age, and mobility (see Staff evolution during the lifecycle of a facility).

The personnel statistics of similar infrastructures are the main source of information for forecasting the stream of flows of different incoming students, i.e. undergraduates, PhD students, fellows, and postdoctoral researchers. Instead, the median gross annual salary associated with the different labour markets that the former infrastructure's students enter after their study career

[58] In this study the rate of return to education is based on multivariate (OLS) analysis from the International Social Survey Programme (ISSP). In particular, in this table we report OLS estimates using potential experience (age minus education leaving age).

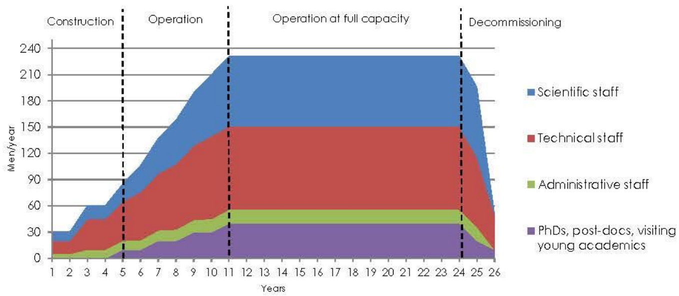
[59] In this study the private internal rate of return is defined as the discount rate that equalises the real costs of education during the period of study to the real gains from education thereafter. For more details on methodology adopted see Blöndal et al. (2002):19.

[60] In this study private return are calculated follows the approach developed in De la Fuente and Jimeno (2005), combining the discount method and the estimation of Mincerian wage premia and other labour market premia from micro-level data. For more details on methodology adopted see Boarini and Strauss (2007):8 et seq..

[61] See www.ramiri-blog.eu.

can be derived from national or European statistics (e.g. the European Community Statistics on Income and Living Conditions – EU-SILC).

Figure 5. Staff evolution during the lifecycle of a facility



Source: Authors based on RAMIRI project handbook.

In practice, the following operational steps can be applied to estimate the human capital benefit:

- Forecast the number of incoming young researchers by category (e.g. Master students, PhD students, fellows, post-doctoral researchers);
- Assume the possible professional sectors in which students leaving the infrastructure are expected to find a job, such as in other research centres, in the academia, and in different industry sectors;
- Assume the probability distribution of different categories of students who find a job in the previously identified professional sectors;
- Estimate the median gross annual salary for each of the identified professional sectors at different career levels (entry level, mid-career, experienced, late career);
- Use an appropriate (e.g. logarithmic) function to estimate the continuous salary curve for each professional sector; and,
- Estimate the 'premium' salary associated with having spent a training period at the considered RDI infrastructure, i.e. the incremental earnings compared with the average salary curve previously described.

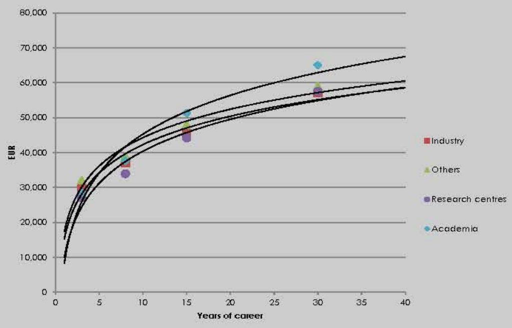
7. Social value of human capital formation

A public sector supported research laboratory in the green biotechnology field is one of the top European institutes in terms of reputation. A project of enlarging it has been proposed, and it is based inter alia on the following assumptions:

- the project time horizon is 15 years ;
- it will host additional 15 PhD students every year for a training period of two years;
- and will host 10 Post-docs every year for a contract period of three years;
- after their training period, students and post-docs are expected to immediately enter the labour markets. In particular, students are supposed to enter four possible professional sectors with the following probabilities:

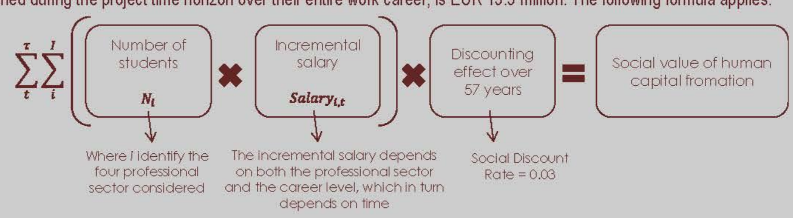
Professional sector	PhD students	Post-doc students
Academia	20%	40%
Other research centre in biotechnology	30%	30%
Biotechnology industry	30%	20%
Other industry (including of chemical, medical and pharmaceutical industries)	20%	10%

- the salary curve associated with the four possible future professional careers are those presented in the graph below;



- based on statistical information, a salary premium of 5 % over the total future salary is expected for students having spent a training period at the considered laboratory as compared to their peers who have not enjoyed the same experience;
- a work career of 40 years.

The expected total discounted human capital benefit, estimated as the present value of the total annual gross incremental salary gained by all students trained during the project time horizon over their entire work career, is EUR 15.5 million. The following formula applies:



5.7 Knowledge outputs and their impact

For scientists and researchers, particularly academics, one of the main benefits to working at a RDI infrastructure is the opportunity to access and process new experimental data, to contribute to the creation of new knowledge, and – ultimately – to produce scientific output that may take the form of technical reports, proceedings, preprints or working papers, articles in scientific journals, and research monographs.

The peculiarity of the RDI infrastructure is that the demand for the knowledge creation function of a RDI project is driven by scientists and researchers in a given field(s) who are often simultaneously users and producers of knowledge. This fact implies that when scientists and researchers spend time on a project, they have an opportunity cost from not working on an alternative project. If this opportunity cost is assumed equal to the average scientist's hourly compensation, a reasonable proxy of the value of scientific output is its marginal scientific cost. This marginal scientific cost represents the time spent by scientists to conduct research and produce knowledge outputs valued at appropriate shadow wages. Hence, the social benefit related to the production of scientific publications can be valued using their *marginal production cost*.

Clearly, not all scientific output has the same value for the relevant community. For this reason, weighing the influence of a paper by multiplying the value of the scientific publications *by a multiplier of impact* is advisable and entails the social value attributed to the degree of influence of that piece of knowledge on the scientific community. In other words, the multiplier captures the additional value attributable to citations that the outputs receive. However, it does not include the indirect social benefits of knowledge that are either accounted for under other items or completely uncertain and set to zero.

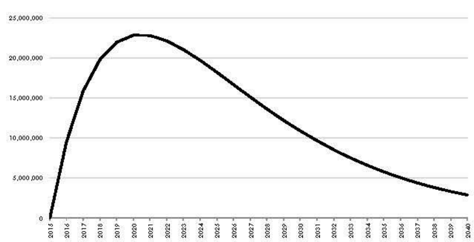
Given $\mathbb{E}(Y_t)$ as the expected social cost of producing knowledge outputs at time t, s_t as the discount factor (shadow cost of production), and $\mathbb{E}(m)$ as the expected multiplier of impact, the expected present value of this benefit is expressed as:

$$\mathbb{E}(O) = \sum_{t=0}^{\mathcal{T}} \left(s_t \cdot \mathbb{E}(Y_t) \cdot \mathbb{E}(m)\right).$$

Empirics

The ex-ante estimation of this benefit involves two operations. The first operation is the estimation of the social value of producing new knowledge as embodied in technical reports, proceedings, preprints or working papers, articles in scientific journals, and research monographs. The second operation is the estimation of the multiplier of impact, i.e. a synthetic multiplicative factor capturing the social value attributed to the degree of influence of that piece of knowledge on the scientific community. These two operations can be synthesised using an appropriate function of time. For example, among different forms, a double-exponential model is described by the formula (see Bacchiocchi and Montobbio, 2009):

$$O = Y_t\, \alpha\, \exp\left(-\beta_1(\mathcal{T} - t)\right)\left(1 - \exp\left(-\beta_2(\mathcal{T} - t)\right)\right),$$



where the expected value of knowledge outputs produced by a RDI infrastructure depends on:

Y_t, the social cost of producing knowledge output;

$\mathcal{T}$, the total number of years for which the number of papers is estimated;

t, the number of remaining years from a given year to the end of the simulation period;

α, a combination of a set of multiplicative parameters representing the characteristics of the scientific community (number of authors, summary measure of their productivity, and others); and,

β_1 and β_2, two parameters that determine the shape of the curve that changes according to the papers weights, distinguishing between excellent and mediocre papers.

To fit the equation parameters, bibliometric[62] techniques analysing the patterns of the scientific literature generated over time around a similar RDI infrastructure or its experiments can be conveniently exploited to associate a measure of scientific output to the RDI infrastructure[63]. However, note that although the use of bibliometric techniques is a well-established approach to provide a quantitative characterisation of scientific activity, relying on publication records available in online repositories may lead to bias when the dominant mode of production in a specific scientific domain is not the journal article. The limited coverage of particular scientific fields by reference databases is a well-known issue in some specific disciplines, such as social sciences and humanities (see Hicks, 2004 and Nederhof, 2006), law, and computer science in which peer-reviewed conferences are a major form of communication. This issue must be carefully taken into account when dealing with the evaluation of the considered benefit and, if necessary, bibliometric analysis needs to be complemented by a detailed analysis of unpublished scientific outputs. Also, attention should be paid to not double counting articles. Actually, in some scientific field such as theoretical physics, exper-

[62] Biblometrics is the discipline dealing with citation data and the statistics derived from them.
[63] These techniques are discussed in Carrazza *et al.* (2013).

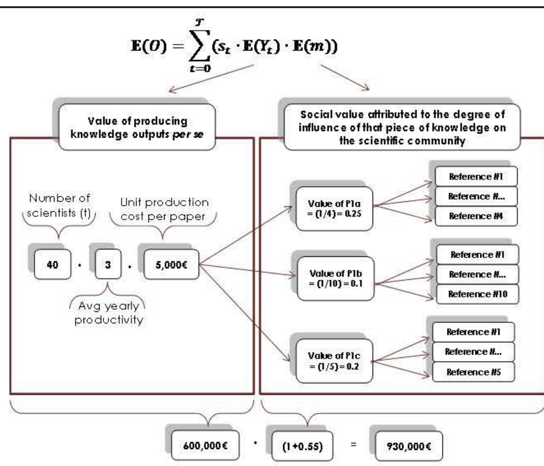
imental physics, materials, engineering the same article is often produced in several different versions (same contents, different titles, and different publication channels).

Box 11. The diffusion of knowledge outputs

According to the literature, curves describing the dynamics of knowledge diffusion over time can be proxied using citation curves. Citation patterns can vary significantly depending on the document studied. Some articles may never be cited, whereas others receive citations in the years immediately after publication and before becoming obsolete. Additionally, some articles may remain rarely cited in the years following their publication, but then become recognised (Andrés, 2009). A 'typical citation curve' describes the history of an article that receives a few citations in the first subsequent years after publication, then peaks, but subsequently is gradually less cited (Sun et al., 2015; Larivière et al., 2008). In some cases, lognormal functions best fit typical citation curves (Egghe and Rao, 1992). Most studies on obsolescence find that the use of the literature declines exponentially with age, and parameterise this phenomenon with a single number, often called the 'half-life' (Burton and Kebler, 1960). However, some argue that an exponential increase in citations is sometimes recognisable over a long period, thereby leading to an exponential function (Li and Ye, 2014).

An operational shortcut to estimate the social value of knowledge outputs consists of a series of steps, as concisely presented in *Figure 6*. In what follows, the data and computations required for each step are discussed.

Figure 6. Social value of scientific output



Note: (*) The benefit is valued through the time that scientists took to read and understand someone else's paper and to decide whether or not to cite it, which is assumed to be one hour. (**) The number of papers, P1, citing parent one is forecasted by reviewing the median number of citations of scientists involved in the infrastructure.

Source: Authors.

First, forecasting the knowledge production capacity of the infrastructure is needed and involves:

- Forecasting the number of scientists working at the infrastructure over the time horizon; and
- Forecasting scientists' yearly average productivity, i.e. the average number of knowledge outputs per author per year. Clearly, predicting the number of knowledge outputs produced within the RDI infrastructure can be influenced by the standards of the personnel expected to be recruited and by the scientific field. Hence, the scientists' yearly average productivity and the average number of authors per paper may largely differ from one discipline to another due to different practices in use. In case of multiple authorships, the main difficulty when estimating average productivity[64] is the definition of the individual contribution[65] to an article.

The second step consists of estimating the value of a scientific output in money terms. In applied welfare economics using marginal costs to estimate the output value is well established, and even in the international accounting convention on GDP public sector costs are used to estimate the contribution of government to the product of a country. The unit production cost per

[64] For a review of the literature on scientists' research productivity, see IVA (2012).

[65] Attention should be paid to two opposed situations. Experiment collaboration articles are typically signed by the so called "authorlists", i.e. persons who did not directly contribute to the contents of the article. Conversely, in other cases articles are only signed by the persons who wrote the article, although many more persons contributed to the work. In both cases, the authors' productivity can be distorted if these aspect are not appropriately reflected in the calculation.

knowledge output may be estimated using the ratio of the gross salary of the author over the number of scientific outputs produced per year. Clearly, only the salary amount for the time dedicated to research within the infrastructure should be considered.

Data on scientists' salaries according to different scientific fields are found in various country-specific or worldwide databases. Table 9 provides illustrative benchmarks for different scientific fields and countries.

Table 9. Examples of scientists' annual salary

Country	Scientific field and experience degree	Benchmark values (EUR)	Reference year	Source
Austria	All fields – senior researcher	Median 66,038	2010	Ates and Brechelmacher (2013)
Finland	All fields – senior researcher	Median 48,387	2008	Ates and Brechelmacher (2013)
France	All field	Average 49,332	2011	Altbach et al. (2012)
Germany	All fields - Entry-Level Research Scientist	Median 48,677	2015	PayScale (2015)
Poland	All fields - senior at university	Median 32,078	2010	Ates and Brechelmacher (2013)
United States	Biotechnology	Median 64,932	2015	PayScale (2015)
United States	Material science	Median 74,744	2015	PayScale (2015)
United States	Clinical research	Median 59,504	2015	PayScale (2015)

Source: Authors based on cited sources.

The third step consists of forecasting the median number of citations per scientific output.[66] The median value is considered a more accurate indicators instead of the average number of citations. Also, an analysis of the median individual h-index of scientists involved in the infrastructure, which captures the *n* number of articles that have received at least *n* citations, could be useful (see H-index vs individual H-index).[67]

As revealed by Table 10, the citation statistics show high variability in different scientific domains[68]. This variability results from different factors. For instance, the chance of being cited is related to the number of publications (and the number of scientists) in the field (Moed et al., 1985); thus, small fields attract fewer citations than more general fields (King, 1987). Therefore, bibliometric comparisons should be conducted only within a field unless a normalising factor is applied.

Box 12. H-index vs individual H-index

The h-index was proposed by Hirsch (2005) with the aim to provide a robust single-number metric of an academic's impact by combining quality with quantity. A scientist has an h-index equal to n if n of his or her papers have at least n citations each and the other papers have no more than n citations each. Hence, a scientist with an h-index of 20 has produced 20 articles with at least 20 citations each.

A number of studies addressed the attempts to correct the h-index for the number of co-authors (see, for instance, Batista et al. (2006) or the alternative provided by the Publish or Perish software program), the scientific field (see, for instance, Iglesias and Pecharromán, 2007); Radicchi et al., 2008); and Malesios and Psarakis, 2012), and the recentness (see, for instance, Sidiropoulos et al., 2006).

In particular, if the h-index is corrected for the number of co-authors, the resulting metric is called the individual h-index. According to the literature, the two indexes shows differences between disciplines. As an example, Table 10 presents the analysis provided in Harzing (2010).

Table 10. Metrics comparisons across disciplines

Scientific field	Average H-index	Average number of authors	Individual H-index
Cell biology	24	3.90	15
Computer science	34	2.57	22
Mathematics	15	2.95	8

[66] It should be acknowledged that estimation of scientific outputs based on citations is somehow problematic in some fields such as theoretical and experimental physics, material and engineering for two main reasons: 1) the science does not work with referencing other papers frequently due to text size limitations; and 2) the same article is often produced in several different versions (same contents, different titles, different publication channels).

[67] Moreover, the h-index is considered a conservative measure that avoids incurring an overestimation of benefits. Indeed, the proposed framework assumes that an article has been accessed and read before being cited, but this may not be true. In some cases, citation data may overstate the extent to which the scientific literature has been consulted. In fact, an author may cite from the abstract of an article or simply copy a reference from another paper (Simkin and Roychowdhury, 2007; Broadus, 1983).

[68] Citations' skewness was identified early on by Price (1965).

Pharmacology	39	3.08	23
Physics	30	2.66	18

Source: Authors based on analyses presented in Harzing (2010).

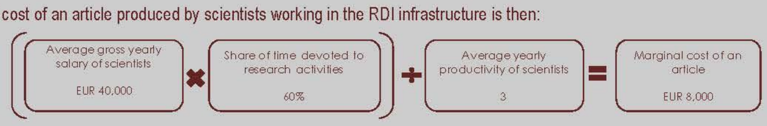
The fourth step consists of assigning a monetary value to citations by deriving the value from the time scientists need to download, read someone else's paper, and decide to cite it[69]. When estimating the value of an article (P1) that cites a scientific output (P0) produced by a scientist within the considered RDI infrastructure, that other articles beyond P0 have contributed to the production of P1 should be considered. This consideration is reflected in the number of references included in P1. Thus, the value of P1 attributable to P0, i.e. the time needed to read and cite P0, must be divided by the number of references contained in P1.

8. Social value of publications

A new integrated network of ten marine biological stations in different coastal locations will be constructed and provided with state-of-art equipment. On average ten scientists will be employed in each facility for the entire operational period (16 years). Given the field, and the track record of existing similar infrastructures in other countries:

- the expected average yearly productivity of scientists within the infrastructure is 3 articles;
- the average time devoted to research is 60% (the remaining time is devoted to teaching and administrative issues);
- the average gross yearly salary of scientists using the infrastructure is EUR 40,000;

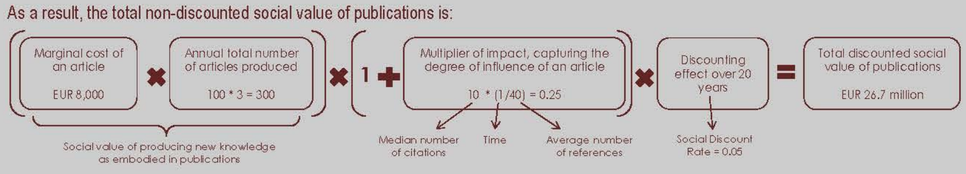
The marginal cost of an article produced by scientists working in the RDI infrastructure is then:



Moreover, according to bibliometric analysis and field experts' opinions, the following information holds:

- the median number of citations of scientists expected to work in the infrastructure is 10;
- the average number of references in the scientific field is 40 per paper;
- the time needed to evaluate someone else's paper and decide to cite it is 1 hour;

As a result, the total non-discounted social value of publications is:



5.8 Provision of services

Some RDI infrastructures provide services to external users, including industries, governmental bodies, and other research teams. These users may pay a fee for accessing and using the infrastructure's equipment and/or specific services offered by the facility for research or technological development and testing purposes.

Services provided by RDI infrastructures may include, among others, machine time, computing resources, software, data, communication, sample preparation, access to archives or collections, education and training, expert support, and analytical services. Some examples are provided in Table 11.

Table 11.Examples of services offered to external users by RDI infrastructures

Infrastructure	What does it offer?
NASA Glenn Research Center (https://facilities.grc.nasa.gov/using.html)	It provides ground test facilities for/needing: Acoustics; Engine Components; Full-Scale Engine Testing; Flight research; Icing research; Microgravity research; Space power and propulsions; Wind tunnels. In addition, a range of test consultation services are offered.
European Synchrotron Radiation Facility (http://www.esrf.eu/Industry/applications)	It provides synchrotron light and techniques (e.g. of imaging, microtomography, topography, microscopy RX and FTIR microscopy) which have many industrial applications. For instance, pharmaceutical and biotech companies use synchrotron techniques to help develop new products at all stages of research, from drug design and formulation to pre-clinical phases. Automotive industries use synchrotron techniques to obtain more efficient catalytic exhaust converters. The synchrotron techniques are also commonly used for the study of inclusions in surfaces or identification of a defect on silicon wafers used to produce semiconductors.
High Magnetic Field Laboratory in	Access to the facility is given to all researchers which have their research proposal for access granted by an

[69] For simplicity, the time needed to download, read someone else's paper, and decide to cite it can be set equal to one hour.

The Netherlands (http://www.ru.nl/hfml/facility/access_to_the)	external review committee. Access involves the use of the installation, the use of all available auxiliary equipment and (if necessary) support of the local staff.
Laserlab-Europe (http://www.laserlab-europe.net/transnational-access)	The 20 laboratories under the Consortium offer access to their facilities for European research teams. Access is provided: to world-class laser research facilities, to a large variety of inter-disciplinary research, including life sciences, free of charge, including travel and accommodation. Access is provided on the basis of scientific excellence of the proposal, reviewed by an external and independent Selection Panel. Priority is given to new users. A typical access project has a duration of 2 to 6 weeks.

Source: Authors based on information retrieved from facilities' websites.

Typically, customers contact the facility manager and, after reviewing the requests, the infrastructure manager provides external users with a cost estimate for a time shift on the machine or the service required. In some cases, the cost estimate by the RDI infrastructure reflects market prices. In other cases – typically when the external users are researchers – the fees charged only cover the costs incurred by the facility to make the service available.

The preferred way to value this benefit is by either using the *long-run marginal cost* of the services provided *or* estimating external users' *WTP for the service*. Alternatively, when market prices are available and are supposed to be non-distorted, i.e. they reflect economic prices, the *nominal (market) prices* can be used.

Empirics

The ex-ante evaluation of this benefit involves the following activities.

- The range of services to be provided by the infrastructure or the amount of time dedicated to commercial uses is forecasted. Benchmarks with similar infrastructures are helpful. As an example, the share of time dedicated to commercial purposes in five European synchrotron radiation facilities is provided in Marks (2007).
- The number of potential external users that may be interested in exploiting the infrastructure's equipment or services is forecasted. Typically, during the design phase of a RDI infrastructure, the promoters investigate external users' interests through surveys. The data collected can be exploited for the forecast.
- The economic value of the services offered is estimated. The long-run marginal cost of the services can be proxied by the costs incurred by the infrastructure to make the services available. Alternatively, external users' WTP for the services can be estimated using contingent valuation methods. When market prices exist for similar services offered by a similar infrastructure, they could be exploited, provided they are not distorted.

9. Benefit from services provided to third parties

A new laser facility is planned and will be operational for 15 years. Among others, the laboratory will offer free access to a complete line of ultrafast lasers and experimental set-ups for high-intensity laser-matter interaction. According to preliminary forecast performed by the project promoters, the following holds:

- based on estimated economic production cost, the beam time costs is EUR 2,000/hour;
- the total hours of beam activity is 3,780 per year;
- the yearly share of beam time dedicated to third-parties access is 10%.

In a deterministic model, the total discounted benefit for the laser provision to third-parties, valued at the marginal cost, is then:

5.9 Social benefits of RDI services for target groups of consumers

Infrastructures for applied research and development are expected to use new knowledge to deliver innovative services and products addressing specific societal needs, e.g. tackling climate change, finding new ways to ensure energy security and efficiency, reducing environmental pollution, mitigating the risk of natural disasters, improving health conditions. Therefore, benefits arise to users who are better off by the delivery of the innovative service or product.

This category of benefits refers only to applications that fall within the infrastructure mission since its funding decision. Situations in which the practical use of a good can be, in principle, expected but is still unknown (in the technical sense, that a probability distribution function is unknown) and cannot be considered under this category of benefits because forecasting and estimating ex ante are not possible. In the latter case, the benefit value is determined by what is generally called 'quasi-option value'. Further elaboration on this issue is provided in the next section on 'non-use benefits'.

The methods to quantify and value the set of benefits derived from the practical application of a research effort depend on the type of innovative service or products made available by the infrastructure. However, these methods are generally based on the willingness to pay or avoided cost approaches and may refer to the more traditional CBA approaches developed for specific sectors. Table 12 presents - as illustrative examples - the evaluation methods referring to typical benefits in the environmental, energy, and health sectors[70].

It is worth noting that the most challenging aspect in the estimation of such benefits is not the translation in monetary value, which usually draws upon well-known and established methodologies and techniques, but the quantification of the amount of benefits. Indeed, given the innovative nature of the supplied service/product, the reach, magnitude and extent of the actual materialisation of benefits is highly uncertain. Hence, what is challenging is forecasting the probabilities of success and the different levels of effectiveness associated to the innovation implemented. In this context, different scenarios – at least one pessimistic and one carefully optimistic – should be forecasted, and each of them needs to be carefully tested through a risk assessment.

[70] This list is not intended to be exhaustive.

Table 12. Examples of social benefits derived from the practical application of a research

Benefit	Evaluation methods	References
Reduction of GHG and air pollutant emissions	To estimate the externality of greenhouse gas (GHG) and pollutant emissions[71], the usual approach consists of *quantifying the emissions avoided because of the project* (measured in kg per tonne of waste) *and valuing them with a unit economic cost* (measured in Euro per kg emission). However, when a new eco-friendly technology is developed and sold to enterprises, for example, the selling price could already incorporate the environmental benefit. In such a case, the externality should not be estimated to avoid double counting.	• IMPACT study (European Commission, 2008), which lists unit cost values for the main relevant air pollutants (in Euros per ton) on the basis of HEATCO[72] and CAFE CBA[73] reports; • NEEDS Integrated Project[74], which provides unit damage costs for air pollutants from emerging electricity generation technologies. NEEDS also provides reliable cost factors for ecosystem and biodiversity damage from air pollution; • Extern-E study[75] provides the unit values of air pollutants produced by energy infrastructures in EU member states. • Teichmann, D. and Schempp, C. (2013). 'Calculation of GHG Emissions of Waste Management Projects'. JASPERS Staff Working Papers.
Improved energy efficiency	The improved energy efficiency benefit is valued through the *decrease in energy costs*, whether incurred by the energy producer, distributor, or final user. The cost reduction is not expressed at market prices, but by considering *the opportunity cost* (shadow price) *of the avoided energy sources*, which should be calculated as the long-run marginal cost of production and (if relevant) transportation. Note that producing electricity from a renewable source could be, at least initially, more expensive than from other sources. In fact, emerging renewable technologies are typically not competitive with fossil fuel alternatives (HM Treasury, 2006). Thus, the project would produce a cost and not a benefit. However, this cost would be (partly or fully) compensated from higher benefits from reduced GHG and pollutant emissions.[76]	• European Commission (2014) chapter 5 on Energy sector. • EIB (2013) contains a chapter on Energy Efficiency and District Heating. • ENTSOE (2015) Guideline for Cost Benefit Analysis of Grid Development Projects. • World Health Organisation (2006). Guidelines for conducting cost-benefit analysis of household energy and health interventions, by Hutton G. and Rehfuess E., WHO Publication • Clinch, J.P. and Healy, J. D. (2001). 'Cost-Benefit Analysis of Domestic Energy Efficiency', *Energy Policy*, 29(2): 113-124.
Reduction in vulnerability and exposure to natural hazards	When a RDI infrastructure project is aimed at developing tools and disaster management systems to facilitate disaster resilience and risk prevention and management for natural risks, a benefit from *avoided damage to capital and natural stocks* is expected[77]. The cost of the avoided damages is estimated using information and data contained in risk and hazard maps and modelling. A shortcut consists of adopting the market insurance premiums available for different typologies of risks to proxy the value of the avoided damage to the capital stock. Instead, for assets for which an insurance market does not exist, averaged calculations on the basis of the avoided costs of the public administration for civil protection activities, compensation	• The Word Bank (2003) Building Safer Cities The Future of Disaster Risk contains chapter 3 on Natural Disaster Risk and Cost-Benefit Analysis. • Guha-Sapir, D. and Santos, I. (2013) *The Economic Impacts of Natural Disasters*. New York, NY: Oxford University Press. • MMC (2005). Natural Hazard Mitigation Saves: An Independent Study to Assess the Future Savings from Mitigation Activities. Volume 2-Study Documentation. Washington DC: Multi-hazard Mitigation Council. • Benson C. and Twigg, J. (2004). 'Measuring mitigation: Methodologies for assessing natural

[71] Examples of pollutants are nitrogen oxides (NOx), sulphur dioxide (SO_2), particulate matter (PM10 and PM2.5), non-methane volatile organic compounds (NMVOC) as a precursor of ozone (O_3), and ammonia (NH_3).
[72] European Commission (2004).
[73] Clean Air for Europe (CAFE) Programme, at: http://ec.europa.eu/environment/archives/cafe/activities/pdf/cafe_cba_externalities.pdf.
[74] New Energy Externalities Development for Sustainability www.needs-project.org.
[75] www.externe.info.
[76] This do not hold true for project within the EU ETS - Emissions Trading System.
[77] The estimation of this benefit involves two main sources of difficulties. First, predicting when an actual disaster will occur and at what intensity is not always possible. Second, the effectiveness of the investments is estimated through vulnerability assessments that include a degree of uncertainty. Therefore, the avoided damages are probabilistic, at best.

	paid to citizens, relocation of buildings, and other activities should be carried out and added to the economic analysis (European Commission, 2014). Alternatively, the people's WTP for decreasing the vulnerability and exposure to a natural hazard could be estimated. Finally, when the project addresses natural assets, additional effects should be evaluated in terms of increased use or non-use values. Regarding use values, the typical additional effects to be considered are increased recreational value (typically valued through the Travel Cost Method) and preservation of productive land (typically valued through its opportunity cost). Regarding non-use value, the preservation of a natural asset in good condition must be estimated by eliciting its existence value (typically through contingent valuation or benefit transfer)[78].	hazard risks and the net benefits of mitigation - A scoping study'. Geneva: International Federation of Red Cross and Red Crescent societies / ProVention Consortium. • Kunreuther, H. and Michel-Kerjan, E. (2014). 'Economics of natural catastrophe risk insurance', in *Handbook of the Economics of Risk and Uncertainty*, Volume 1, MJ Machina and WKViscusi (Eds), Elsevier.
Improved health conditions	Changes in human mortality and morbidity rates can be triggered by a RDI infrastructure[79] with different aims, such as improving the health conditions of the people affected by a certain disease by producing a new drug or an innovative treatment technology; improving the health safety of people (or a group of people), such as through food and transport; remediating a polluted environment, e.g. a radioactive dump or a site contaminated by chemical waste; and mitigating the risk of natural disasters. In such cases, the project's marginal benefit is the reduction in mortality or morbidity rates, or improved health conditions. Following the literature, these reductions can be valued using the Value of Statistical Life (VOSL), defined as the value that society deems economically efficient to spend on avoiding the death of an undefined individual. The Quality Adjusted Life Year (QALY) may also be used, which measures the value of a change in both life expectancy and quality of life. The preferred approach to value changes in health outcomes is to calculate the willingness-to-pay of people affected by the project. This calculation can be done using the stated preference methods (surveys) or revealed preference methods (hedonic wage method). However, in practice, the human capital approach (for mortality) or the cost of illness approach (for morbidity) is more frequently used. Each method has benefits and drawbacks.	• On Value of Statistical Life, see for instance: Landefeld and Seskin (1982); Viscusi and Aldy (2003); Abelson (2008 and 2010), Sund (2010); and Viscusi (2014). • On Value of a Life Year, see for instance: Johannesson and Johansson (1996), Chilton et al. (2004) and Desaigues et al. (2011). • For a major meta-analysis of Value of Statistical Life estimates, derived from surveys that asked people around the world about their willingness to pay for small reduction in mortality risks, see OECD (2012) or Lindhjem et al. (2011). • For a meta-analysis of Value of Statistical Life estimates, derived from revealed preference studies, see Mrozek and Taylor (2001). • On human capital approach see for instance Landefeld and Seskin (1982) and Brent (2003, chapter 11. • On the cost of illness approach see for instance Rice (1967) and Rice at al. (1985) and Byford et al. (2000). • World Health Organisation (2006), Guidelines for conducting cost-benefit analysis of household energy and health interventions, by Hutton G. and Rehfuess E., WHO Publication.

Source: Authors.

[78] Some examples of existence values retrieved from the literature are provided in Table 13.
[79] Or project is carried out within the RDI infrastructure.

10. Benefit of CO2 reduction

A research-based biotechnological company in collaboration with a university laboratory wants to develop an innovative enzyme to enhance energy efficiency in detergent industries. In particular, the enzyme-driven industrial processes is expected to reduce the carbon dioxide emissions from 300 kg to a range of 40-80 kg every tonne of product produced (baseline value = 50 kg/tonne).

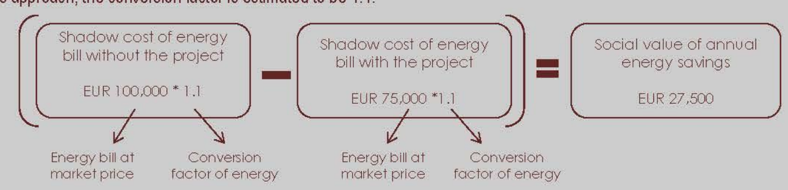
Assume there are 20 cosmetic plants interested in using the new enzyme (which will become obsolete in 10 years) and that each of them produce 100 tons of products per year. If the shadow price of CO2 is EUR 35/tonne, the total benefit for reduction in CO2 emission in a deterministic model is then:

In a pessimistic scenario, the carbon dioxide emissions are 80 kg/tonne of product produced, thus the total discounted benefit is EUR 110,016. Instead, in an optimistic scenario, the emissions are 40 kg/tonne and the total discounted benefit is EUR 130.019. Taking 40 and 80 as the lower and upper bounds of a triangular probability with modal value equal to 50 kg/tonne, the expected benefit of CO2 reduction can be calculated through a Monte Carlo simulation.

11. Social value of energy saving new technology

A laboratory meant to develop a new technology which allows reduced energy-consumption costs to keep the temperature inside high temperatures process used in the primary metals industry at the same level as in the without-the-project scenario. It is assumed that an energy bill of EUR 100,000 is annually paid by the manufacturing plants potentially interested in the new technology which corresponds to a steady temperature of 2500 K. After the new technology's implementation, the energy efficiency of the manufacturing plants increases and this is reflected in a decrease of annual energy costs (to EUR 75,000) that is required to maintain the same required temperature.

In the economic analysis, the opportunity cost of energy should be considered, by applying a conversion factor to the cost saving. Based on border prices approach, the conversion factor is estimated to be 1.1.



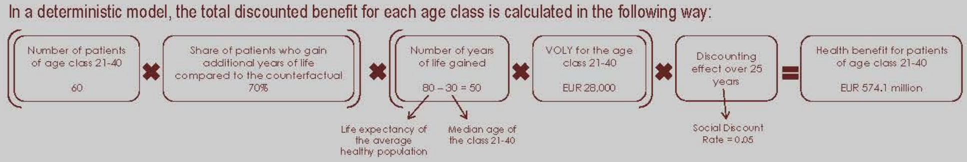
12. Benefit from increased life expectancy

An applied research infrastructure specialised in hadrontherapy, an advanced oncological treatment showing clinical advantages as compared to traditional radiotherapy and exploiting accelerator technology, is planned. The facility will provide health treatments to patients affected by some other fatal types of solid cancer, for whom gains in terms of longer or better lives are expected as compared to a counterfactual situation where they are treated with conventional therapies. Health improvements related to patients affected by chordomas and chondrosarcomas of the skull base are considered. According to forecasts made by project promoters, the following holds:

- during routine operation nearly 300 patients affected by chordomas and chondrosarcomas of the skull base will be treated every year. In particular, 60 patients per year are expected under six classes of age with median age corresponding to 10, 30, 50, 70 and 90 years.
- no alternative treatments are available for patients affected by chordomas and chondrosarcomas of the skull base;
- the marginal percentage of patients who fully recover compared to the counterfactual situation is 70%. This means that 70% of total treated patients thanks to hadrontherapy gains the same life expectancy of the average healthy population (80 years);
- following the human capital approach, the VOLY values for each of the six classes of age identified has been calculated. Namely:

Age class	VOLY
10 (1-20)	29,000
30 (21-40)	28,000
50 (41-60)	27,000
70 (61-80)	26,000
90 (81-100)	25,000

In a deterministic model, the total discounted benefit for each age class is calculated in the following way:



Aggregating the discounted health benefits related to all the age classes, the total discounted benefit stemming from the infrastructure is calculated.

5.10 Recreational benefits for the general public

Some RDI infrastructures, in particular but not only large-scale ones, have an outreach strategy to attract the interest of the general public, such as through the organisation of permanent or temporary exhibitions, open days, or guided tours – typically for free or at a modest price. For instance, large research infrastructures follow such a strategy, including the Daresbury Synchrotron Radiation Source in Cheshire (UK), the Kennedy Space Center (KSC) Visitor Complex in Florida, the CERN in Geneva, the Max Planck Institute for Plasma Physics in Greifswald (DE), the High Magnetic Field Laboratory in Nijmegen (NL), and the European Southern Observatory in the Atacama Desert of northern Chile.

The ultimate beneficiaries of outreach activities are visitors to the infrastructure. In line with standard CBA approaches in the cultural economics sector[80], the expected marginal social value of this benefit is the expected visitors' implicit willingness-to-pay for a visit. Hence, the following formula applies:

$$\mathbb{E}(R) = \sum_{i=1}^{I} \sum_{t=1}^{\mathcal{T}} s_t \cdot \mathbb{E}(W_{it})$$

where W is the user-benefit of general public individuals ($i = 1, \dots I$) for visiting the RDI infrastructure.

In addition to in-person visits, participating in activities on social media, in television audiences, and through websites are further indicators of the size of the cultural impact produced by the infrastructure. When relevant, the cultural benefits enjoyed by virtual visitors should be considered as well.

[80] See, for instance, Clawson and Knetsch (1966); Caulkins et al. (1986); Cuccia and Signorello (2000); and Bedate et al. (2004).

 Confidential

Empirics

The ex-ante estimation of the benefit enjoyed by personal onsite visits involves:

- Forecasting the number of visitors over the time horizon; and,
- Estimating the willingness-to-pay for a visit. As with recreational sites, the standard way to estimate the WTP is using the travel cost method (see box below) or the benefit transfer approach[81]. In the economic analysis, that the WTP replaces any possible revenues from visitors included in the financial analysis is worth noting.

Box 13. The travel cost method

The travel cost method (TCM) was suggested by Hotelling (1947) and developed by Clawson and Knetsch (1966) to assess the value of environmental resources and recreational sites[82]. TCM has also gained popularity in cultural economics, particularly regarding cultural heritage[83]. The method attempts to place a value on a non-market good by drawing inferences from expenditures incurred to 'consume' it, including the cost of the trip (e.g. fuel, train, or airplane ticket), the opportunity cost of time spent travelling, entry fees, on-site expenditures, and accommodation costs.

In particular, two types of TCMs exist: the 'individual demand approach' and the more common 'zone of origin approach' (Anex, 1995). The latter is the simplest and least expensive approach and is applied by collecting information on the number of visits to the site from different distances. This information is used to construct the demand function and to estimate the economic benefits for the recreational services of the site. Instead, the individual demand approach uses survey data from individual visitors in the statistical analysis rather than data from each zone.

Although widely adopted, the TCM is affected by a major limitation that should be carefully addressed. The limitation is related to the apportionment issue arising whenever it is reasonable to assume that a trip is made for different reasons (a multi-purpose trip) and not to visit a specific RDI infrastructure. Actually, disentangling the willingness to pay of visitors for a given infrastructure when more than one attraction is located in the same site or in the same area could be arduous.

The ex-ante estimation of the benefits enjoyed by virtual visitors involves the following activities.

- The number of virtual visitors is forecasted over the time horizon. First, the possible communication mediums people can use to virtually approach the infrastructure, i.e. social media, website, television, and radio, are established. Second, virtual visitors per type of mean is forecasted through proper techniques commonly used by marketing specialists, such as by using the number of 'tweets' or followers in Twitter, posts or pages in Facebook, subscribers of the YouTube dedicated channel or number of views of a video, estimated number of people watching an event on television, number of blog conversations, volume of web traffic, registrations on the official website, and so on.
- The willingness-to-pay for a virtual visit is estimated[84]. A broadly used method to attach a monetary value to non-market goods is contingent valuation. Contingent valuation consists of asking people to state the maximum amount they would be willing to pay to obtain a good or would accept as compensation to give away a good, contingent on a given scenario. However, empirical studies show that when consumers are accustomed to receiving an online service or content for free, their willingness to pay is very low or nil (see, for instance, Chyi, 2005). Difficulties in obtaining values of willingness to pay through contingent valuation have also been experienced in the cultural sector (Snowball, 2008). In this context, the choice experiment or conjoint analysis methods are considered more useful than traditional contingent valuations. Still based on stated preferences, these techniques imply asking a sample population to choose or rank different combinations of attributes of the same good (e.g. a museum, an archaeological site), for which the price is included as an attribute. This method enables the uncovering of preferences in terms of willingness to pay for each attribute and the entire set to be more effective. The same techniques could be usefully exploited to attempt to value public interest for the RDI infrastructure.

[81] On WTP of recreational sites/activities, see Sorg and Loomis (1984); Pearce (1993); Loomis and Walsh (1997); and Mendes and Proença (2005).
[82] For a review, see, for instance, Garrod and Willis (2001); Hanley and Barbier (2009); and Tietenberg and Lewis (2008).
[83] See, for instance, Alberini and Longo (2005); Bedate et al. (2004); Poor and Smith (2004); and Ruijgrok (2006).
[84] On WTP for social media, see Westland (2010); Han and Windsor (2011); and Vock et al. (2013).

13. Cultural effects of on-site visits

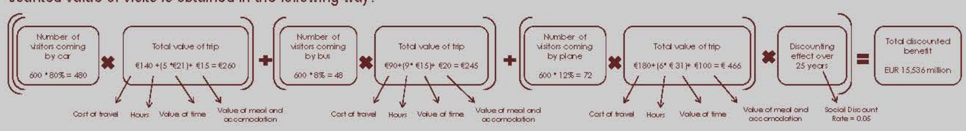
A research facility hosting a particle accelerator is expected to organise 40 guided tours per years for general public. The tours are free of charge. The project promoters have forecasted that the average number of visitors per tour is 15 persons. No revenue from the visitors is recorded in the financial analysis, but the visitors' willingness-to-pay need to be accounted in the economic analysis. According to the travel cost method to estimate the WTP for a visit, the following information need to be collected:

- Breakdown of visitors by origin. According to a sample of experts, 80% of visitors are expected to come from an area with in a radius distance of 200 km and the remaining 20% from a longer distance.
- Breakdown of visitors by transport mode used. Assume that all the visitors coming from an area with radius distance of 200km are expected to travel by car, while the other visitors are expected to travel by bus (40%) or plane (60%).
- Estimate the cost of travel by transport mode. It includes the cost of fuel, tolls and other operating costs if travelling by car. Otherwise it includes the cost of ticket.
- Estimate the value of time spent in travelling. HEATCO reference values for leisure trips can be used.
- Estimate the cost of meals and the possible cost of accommodation for the share of visitors coming from larger distance.

Summing up:

	sport mode	f total visitors	st of travel (A/R)	me (hour)	ue of time	ost of meals and accommodation
200 Km	Car	80%	EUR 140	5	21	EUR 15
200 Km	Bus	8%	EUR 90	9	15	EUR 20
	Plane	12%	EUR 180	6	31	EUR 100

The average WTP for different classes of visitors, i.e. coming from different origins and by different transport modes, is then multiplied to the share of expected number of visitors per year in order to obtain a valuation of the economic benefit. In a deterministic model, the total discounted value of visits is obtained in the following way:

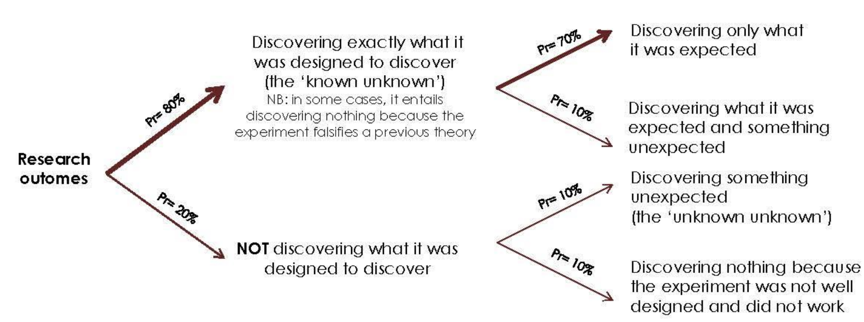


5.11 Non-use benefits: new knowledge as a public good

In most cases, for applied research and innovation infrastructures, the estimation of use-benefits (B_u) should probably be sufficient to justify the worthiness of the infrastructure in CBA terms, i.e. the (ENPV)>0. However, for a basic research infrastructure, an additional impact on social welfare may be related to its discovery potential. The unpredictable and maverick nature of discovery makes estimations of the results possible only in probabilistic terms and only to some extent. Basic research experiments are associated with a broad set of all possible outcomes, usually called the sample space, and each outcome has a probability of occurring (see Figure 7)[85].

[85] In this context, it is worth mentioning that when research hypotheses are not confirmed or designed discoveries do not occur, these results are, nevertheless, valuable and lead to at least the production of knowledge outputs, such as publications.

Figure 7. Illustrative example showing probabilities (Pr) associated with different research outcomes



Note: Pr = probability. Source: Authors

Although the value of publications stemming from such discoveries crudely reflects, in statistical terms, the social benefit to scientists of advancing knowledge within their community, the discovery itself could have an intrinsic social value and could bring a number of further improvements to human wellbeing that have not been accounted for until now. These additional benefits are defined as non-use benefits and are captured by a residual term (B_n) in the present framework. This approach and terminology is borrowed by environmental economics, for which any good or natural resource can be assigned a total economic value[86] that, in turn, can be decomposed into the following two general classes.

- The *use value* refers to the direct or indirect benefits arising from the *actual use* of an asset or its potential or *option use*[87], which indicates the value attached to the future, based on known opportunities.
- The *non-use value* denotes the social value for simply preserving a natural resource compared with not preserving it[88]. Non-use value includes a *bequest value* that arises from the desire to preserve certain resources for the benefit of future generations[89] and an *existence value* related to knowing that a good simply exists even if it has no actual or planned used for anyone and is independent of any altruistic motives[90]. In addition, situations could also exist in which the practical use of a good can be expected in principle but is still unknown. In these cases, its value is determined by what is generally called '*quasi-option value*'.

[86] See Daily (1997); OECD (1999); Turner (1999); and Pearce *et al.* (2006).
[87] The concept of option use value was first introduced by Weisbrod (1964).
[88] The concept of non-use value was first noted by Krutilla (1967).
[89] On 'bequest value', see, for instance, Walsh et al. (1984) and Schuster *et al.* (2005).
[90] On 'existence value', see, for instance, Boyle and Bishop (1987) and Blomquist and Whitehead (1995).

Box 14. 'Option value' vs 'quasi-option value' in the literature

The concept of option value originated in Weisbrod et al. (1964), where he responded to Friedman's (1962) advocacy of a policy of closing down a national park if the commercial value of lumber or minerals exceeded the willingness to pay for the recreational use. Weisbrod et al. (1964) argued that the WTP by recreation users of the park understates its value to society because many individuals expect they may visit the park and would be willing to pay for an option that guarantees their future access. Therefore, option value becomes significant under conditions of uncertainty regarding future demand and/or supply, but when a potential use is identified.

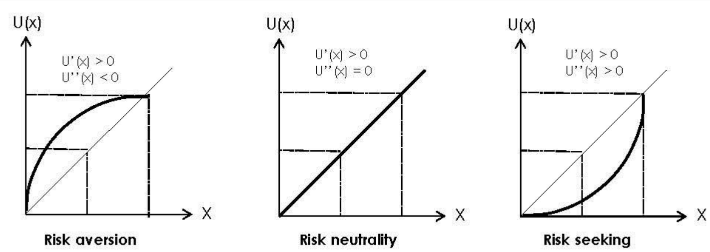
In OECD (2006), the option value is formulated as the difference between the option price, i.e. the maximum WTP expressed now for something uncertain in the future, and the expected value of a consumer's surplus. In the literature, the concept of 'option value' is sometimes considered equal to the 'quasi-option value', which is confusing (Reiling and Anderson, 1980). Although the two values are interlinked and can coincide under certain conditions, they are built on slightly different assumptions, in particular for what concerns the irreversibility condition of the investment decision.

The concept of 'quasi-option value' was introduced by Arrow and Fisher (1974) when studying how the uncertain effects of certain economic activities could be irreversibly detrimental to future environmental preservation. This concept describes the impact of a development intervention in one period on the expected costs and benefits in the next, i.e. the expected net benefits in future periods that are conditional on the realised benefits in the present period. Elaborating on this concept, Conrad (1980) highlighted the notion of quasi-option value as being equivalent to the expected value of information. The value of lost and new options allowed by an investment project implemented today is an expected value based on what one might learn. The same interpretation is found in Atkinson et al. (2006: 21), who defined the quasi-option value as the 'difference between the net benefits of making an optimal decision and one that is not optimal because it ignores the gains that may be made by delaying a decision and learning during the period of delay'. In the context of CBA of RDI, the same definition may apply to the unknown losses that may occur by delaying the same decision. Using the concepts of 'quasi-option value' originally conceived for environmental goods and natural resources to also value other categories of goods is not an entirely new concept. Arrow and Fisher (1974: 319) conceded that the quasi-option value is a general notion that may be applied outside environmental economics because it is linked to uncertainty, information, and irreversibility issues that affect decision making in general.

Retaining this terminology, the term (B_n), i.e. the value of unknown non-use value effects, is determined through the sum of two different components: the quasi-option value (QOV) and the existence value (EXV), while if there is an option value for some specific benefit, this should be included as a use value.

More specifically, a RDI infrastructure may create a quasi-option value in the sense that it could generate discoveries that produce positive impacts that, however, cannot be estimated when the funding decision is made[91]. The irreversibility aspect is that once something is known, destroying such knowledge and going back to the previous state of the world is virtually impossible. Hence, the welfare effect in principle is the opposite of the Arrow-Fisher effect, which claims that quasi-option value leads to similar risk aversion results. In the RDI context, as information is created, the effect is similar to risk seeking, i.e. it increases the value of a project because it has the chance to discover something.

Figure 8. Preferences to risk



Note: First and second derivatives of a utility function related to good x determine the shape of utility and express preference for risk-taking.
Source: Authors.

In general, we expect that QOV is to be considered a benefit. However, in certain cases, the social preference may be not to know something, as reflected in legislation that forbids certain types of research on humans, for either ethical reasons or as a precautionary principle. Given the fact that, in general, the PDF of QOV is unknown, we suggest conservatively setting this component equal to zero. This assumption may be considered excessively prudent but also is consistent with the first principles of CBA. For example,

[91] QOV usually remains completely unknown for a long time, even ex post.

building a new highway may have far-reaching broader effects in the future because the highway may create new opportunities to connect distant people. From this fact, new cultural and economic circumstances may arise. However, our present knowledge of this concept is too uncertain and usually it is not included in the CBA of a highway, i.e. it is implicitly set to zero, even if transport infrastructures in the long run will literally change the world over many dimensions.

In contrast, an *existence value* can be attributed to the discoveries of an RDI infrastructure, reflecting a social preference for pure knowledge *per se*. In other terms, EXV refers to the intrinsic value of knowing the object of the discovery, regardless of the fact that it might find some use sooner or later. Contrary to the QOV which is unknown, preferences for the existence value of discoveries in principle can be detected ex ante. In practice, when $ENPV_u < 0$, the net present value of the non-use benefits, proxied by the EXV of discoveries, should be greater than the net costs for the infrastructure to be deemed socially beneficial[92].

Box 15. 'Existence value' vs 'quasi-option value' in our framework

Quasi-option value and existence value are two distinct concepts with the following main differences.

- In principle, the quasi-option value could be either positive or negative, producing either an increase or a decrease in social welfare. However, we assume that advancing knowledge has at least a zero value and, in general, a positive one, unless for extreme situations in which such knowledge has potentially detrimental uses for society. In fact, the irreversible effect is new knowledge itself. Setting this component to zero represents taking a neutral attitude about unknown uses of new knowledge. Instead, existence value can always be regarded as intrinsically positive or at least nil: people can be expected to be better off or completely indifferent to a discovery, just for the pure value of such knowledge.
- The two concepts have an empirical dimension. The quasi-option value for the unknown effects of a discovery is usually completely uncertain ex ante and, thus, no preferences can be imputed to it as long as the effects remain unknown. However, ex post, the value will be revealed by new information. Instead, people could have some ex-ante preferences about knowing that something is discovered; they are unlikely to have preferences if they do not know or understand the issue at stake. However, if they obtain 'some' information, then assuming that preferences will arise that allow them to choose between two states of the world is reasonable, i.e. one state in which the scientific discovery occurs and one state in which it does not. Indifference is also possible. In the latter case, the existence value is also zero.

Empirics

The standard method for estimating non-use values for which no observable price system exists is to recur to stated preference techniques[93]. In particular, the use of a contingent valuation methodology has found widespread application in environmental economics for estimating the economic value of species and natural resources[94]. In the same vein, one could attempt to grasp the WTP of taxpayers having preferences for having a discovery, regardless of its actual or potential use.

There are two possible objections to contingent valuation[95]. The first objection concerns the cost required to perform a proper contingent valuation exercise. Although this consideration is important, the typical cost per capita of a well-designed contingent valuation is often a modest fraction of the overall cost of the infrastructure in the first place, particularly for the large ones.

A second objection is that asking individuals their WTP for the mere existence of any good may not be easy and may bias the results in a number of individual, cultural, and socio-economic circumstances (Carson and Groves, 2007; Carson, 2012). To address these issues, the evaluator should take into account a number of recommendations developed since the early nineties, particularly those followed by a panel of distinguished economists for the US National Oceanographic and Atmosphere Administration (NOAA, 1993), including indications about the modalities and structure of the interviews. In

NOAA panel guidelines adapted to the RDI infrastructure evaluation context, we slightly adapt the NOAA panel guidelines to our context.

[92] This statement holds true under the reasonable assumption that the EXV is always positive.

[93] Stated preference techniques involve soliciting responses to hypothetical questions regarding the value that people place on goods. Thus, they are based on answers given by a representative sample of the population of interest to derive a respondent's willingness to pay for a good. Within the class of stated preference methods, two main alternative groups of techniques exist: choice modelling and contingent valuation. The latter seeks measures of willingness to pay through direct questions such as, 'What are you willing to pay?' and 'Are you willing to pay €X'? The former seeks to secure rankings and ratings of alternatives from which WTP can be inferred (Bateman et al., 2002).

[94] Empirical studies that used contingent valuation include, for example, Vasely (2007); Togridou et al. (2006); Sattout et al. (2007); Carson (1998); Walsh et al. (1984); and Greenley et al. (1981).

[95] The literature on contingent valuation has debated numerous issues. Reviews of these debates can be found in Carson et al. (2001), Portney (1994), and Mitchell and Carson (1989).

Box 16. NOAA panel guidelines adapted to the RDI infrastructure evaluation context

- The target population should be identified, and could be the entire population of the country (or region) in which the infrastructure is located or a defined group of people in a reference geographical area (world, nation, region). Because new knowledge can be a global public good, in some cases all of humankind is the potential beneficiary, but only tax-payers of some countries would in fact support the project.
- The sample type and size should be identified, which should be the closest practicable approximation to the target population and might consist of, for example, all taxpayers in a region, all students from certain universities, and all subscribers to certain magazines. Appropriate sampling is essential. This selection process involves the use of a randomised procedure.
- Careful pretesting should be done because the interviewers may contribute to 'social desirability bias' in the event that face-to-face interviews are used to elicit preferences. To avoid the bias that certain things may be broadly viewed as something positive, pretesting for the interview effect should be done. Pretesting is also essential to verify whether respondents understand and accept the context description and the questions.
- The purpose of the questionnaire should be stated and an accurate description of the RDI infrastructure, its mission, and research potential should be provided, which ensures that respondents understand the context, are motivated to cooperate, and are able to participate in an informed manner. The use of pictures could help.
- The payment vehicle, i.e. the manner in which the respondent is (hypothetically) expected to pay for sustaining the infrastructure's research activity/mission should be described.
- The elicitation format, for which open-ended, bidding game, payment card, and single-bounded or double-bounded dichotomous choices are the most broadly used formats, should be carefully selected. Dichotomous (i.e. 'referendum-like') valuation questions that allow for uncertainty by including a 'don't know' option are recommended by the NOAA panel.
- Follow-up questions should be inserted, which are essential to understanding the motives behind the answers to WTP elicitation questions.
- Questions allowing for cross-tabulations should be inserted, including a variety of other questions that assist in interpreting the responses to the primary valuation questions. For example, income, education level, prior knowledge of the infrastructure, prior interest in the issue, and attitude towards RDI are items that would be helpful in interpreting the responses.
- Both sample non-response and item non-response should be minimised. A reasonable response rate should be combined with a high but not forbidding standard of information.
- The conservative approach should be preferred: when the analysis of the responses is ambiguous, the option that tends to underestimate WTP is preferred. Similarly, the reliability of the estimate should be increased by eliminating outlier answers that can implausibly bias the estimated values.

Alternatively, to overcome the difficulty of explicitly stating a willingness to pay, in some circumstances, valuation methods based on the revealed preference can be conveniently employed. These methods assume that the existence value can be determined through the observation of economic behaviour in a related market, such as voluntary contributions to organisations devoted to the preservation of a public good. For instance, in the RDI context in some countries, several scientific institutions are supported by taxpayers who can name a charity or a research body to which a percentage of their taxable income is donated (Florio and Sirtori, 2014). Additionally, universities regularly receive donations for research from firms and individuals.

A third approach, not necessarily an alternative to the previous approaches, is to recur to benefit transfers. In this case, a meta-analysis of contingent valuation studies on the existence value of goods produced by other projects is used to establish a benchmark median value or a range of values. If the project is well within the range or in the median to lower bound of the range, the guess is made that the project is as beneficial as other goods for which empirical analysis of an existence value is available (Florio and Sirtori, 2014).

Box 17. The Environmental Valuation Reference Inventory

The Environmental Valuation Reference Inventory (EVRI) is a searchable storehouse of empirical studies on the economic value of environmental benefits and human health effects. The EVRI was developed in the 1990s by Environment Canada (a governmental body) in collaboration with a number of international experts and organisations as a tool to help policy analysts use the benefits transfer approach to estimate economic values for changes in environmental goods and services or human health. Currently, the database makes available more than 4,000 valuation study records contained in more than 30 fields. The main categories in an EVRI record include study reference, study area and population, environmental focus, study methods, a table of estimated values, and an abstract (McComb, 2006). In particular, the EVRI's Searching Module helps the user identify studies with the potential for transfer, whereas the Screening Module helps the user assess the suitability of the studies identified in the search according to criteria outlined in the benefits transfer literature. The EVRI can be visited at www.evri.ca.

As a final remark, attention should be given to the fact that some research projects are much more appealing or in vogue than others, even if less promising in terms of the probability of achieving the designed results. This interest is reflected in the estimate of their existence value regardless of the approach followed. For instance, fighting climate change, finding a remedy for Alzheimer's, and discovering exoplanets are appealing issues that could be attached to higher value relative to other research quests that address less known issues, have less visibility, and have a weaker impact on the general public. This possible bias needs to be taken into account when estimating the existence value of discovery, and the information setting of the contingent valuation should be carefully designed.[96] These examples also suggest that, in fact, WTP as elicited by a CV approach will usually be a blend of perceived QOV and of pure EXV. This fact *per se* is not disturbing, provided that the design and interpretation of the survey results are careful. While there is wide experience of these methods in other fields, experimenting them in the RDI domain will need several adaptations and a learning by doing process. Against a relative modest cost, the advantage of this approach is to elicit tax-payers preferences in quantitate terms, and the correlations with individual and social features, which is *per se* important information in a science policy perspective.

[96] The information and the questions provided in the questionnaire should not have emotionally charged effect.

14. Existence value

A new terrestrial exoplanet research institute equipped with a Large Binocular Telescope Interferometer is planned in country LAMBDA. It will be entirely supported by the national government budget. It has a mission to explore terrestrial bodies and seek out the existence of potential life beyond the confines of our own solar system. The net present use-value of this government-owned research infrastructure is negative: EUR –40 million discounted.

There are however a number of people in the general public interested in discovery of exoplanets, as suggested by website and other media data. In order to elicit people willingness to pay for the potential discoveries the project promoters design and carry out a contingent valuation survey. Specifically, the survey was performed in NOAA-panel referendum format on a random of 600 taxpayers of country LAMBDA (counting a population of 5 million taxpayers) drawn using a simple random selection method in such a way as to be representative of the population. Thanks to the face-to-face interaction, the survey showed a quite high response rate of 80%.

First, respondents have been inquired about their personal and household incomes with the aim to measure their financial means and possible contribution to support the institute. Then, their previous knowledge and interest for the topic of research infrastructure has been investigated before going to the specific case of exoplanet research institute on which a summary information, including visual material, is given. Finally, the willing to contribute to support the potential discoveries of the institute is elicited.

In line with NOAA recommendations, the "No-answer" option was allowed and followed-up by questions with the aim to non-directly explain the choice. The answers to these follow-up questions suggest individuals' rough indifference towards the survey matter. Thus, the "No-answers" were not considered in the calculation of the average WTP. The survey results take the following form:

Classes (EUR per year)	Average EUR per year	Relative frequency
0	0	10%
0.1 - 0.5	0.3	10%
0.6 – 1.0	0.8	45%
1.1 -1.5	1.3	20%
1.6 -2.0	1.8	15%

As an example, summaries of cross-tabulations of willingness to pays and on how important is for the respondent is investing in R&D infrastructure is presented in the following table.

Response category	% with WTP 0	% with WTP 0.3	% with WTP 0.8	% with WTP 1.3	% with WTP 1.8
Not important at all	85%	60%	40%	30%	15%
Slightly important	5%	10%	10%	15%	10%
Moderately important	5%	10%	20%	30%	15%
Very important	0%	10%	15%	15%	30%
Extremely important	0%	5%	12%	8%	25%
Don't know	5%	5%	3%	2%	5%

Statistical inference from the sample to the population of LAMBDA's taxpayers is done. Hence, considering a time horizon of 20 years, the total discounted existence value for the discoveries of the exoplanetary research institute is then:

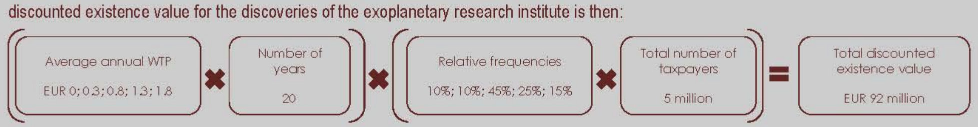


Table 13.Examples of existence value retrieved from the literature

Category	Good	Country	Average WTP (EUR per person, per year)	Source
Cultural goods	British Library	United Kingdom	7.62	British Library (2004)
	Royal Theatre of Copenhagen	Denmark	27.69	Hansen (1997)
	The Arts, Kentucky	USA	3.95	Thompson et al. (2002)
Environment - Habitats	Wilderness areas, Portugal	Portugal	16.64	Nunes (1999)
	Ecological agricultural fields	The Netherlands	9.87	Wiestra (1996)
	Desert protection in California	USA	45.31	Richer (1995)
	Protection of Peat Meadow Land	The Netherlands	25.36	Brouwer (1995)
	Protection of the Kakadu Conservation Zone and national park	Australia	29.25	Carson et al. (1994)
	Grand Canyon	USA	33.32	Pearce (1993)
	Colorado Wilderness	USA	18.40	Pearce (1993)
	Increased forest biodiversity conservation	Finland	81.12	Lehtonen at al. (2003)
	Preserve the Rakaia river in its existing state	Australia	9.21	Sharp and Kerr (2005)
Environment - Single species	Bald Eagle	USA	15.55	Pearce (1993)
	Whooping Crane	USA	1.50	Pearce (1993
	Grizzly bear	USA	23.19	Pearce (1993)
	Coyote	USA	6.59	Stevens et al. (1991)
	Salmon	USA	9.49	Stevens et al. (1991)
	Gray Whale	USA	19.75	Loomis and Larson (1994)
	Wolf in Sweden	Sweden	55.80	Boman and Bostedt (1995)
Environment - Various species	Endangered species in West Germany	Germany	66.64	Hampicke et al. (1991)
	Preservation of 300 endangered species in Sweden	Sweden	125.23	Johnansson (1989)
	All endangered species in Victoria	Australia	46.58	Jakobsson and Dragun (1996)

Source: Authors based on cited sources.

6. The net benefit test

6.1 Estimating the probability distribution of the economic net present value

Once the inflows and outflows (financial and economic) associated with the infrastructure have been identified and their baseline values have been valued in monetary terms, the usual financial and economic performance indicators of the project are computed.

- Similar to financial performance (see section 2.4, 'Financial profitability and sustainability'), the investment's economic performance can be calculated using the following indicators:
- the economic net present value (ENPV), expressed in monetary terms, which is defined as the difference between the discounted total social benefits ($B_u + B_n$) and costs;
- the economic internal rate of return (EIRR), which is the specific social discount rate value that produces an ENPV equal to zero; and,
- the benefit-cost (B/C) ratio, i.e. the ratio between the discounted benefits and costs.

In particular, a project with positive performance, i.e. a project that shows a positive return to society, is associated with the following results:

- The ENPV is higher than zero – the higher the ENPV the larger the social benefits achieved, net of costs and negative externalities.
- The EIRR is higher than the adopted social discount rate.
- The B/C has a value higher than one.[97]

However, from an ex-ante perspective, the probability of an error related to each forecast and estimate included in the analysis should be considered to be high. To address this issue, a full-fledged quantitative risk assessment is required[98], meaning that costs and benefits become part of a probabilistic (stochastic) model instead of a deterministic one. The baseline ENPV is calculated as the discounted sum of a set of 'most likely' (or 'best guess') values, subjectively assumed by the project promoter in accordance with the empirical evidence and given his/her knowledge about the specificities of the infrastructure. Instead, the probabilistic model requires assigning each critical variable a specific probability distribution. As a result, the probability distribution of the outcome of interest, i.e. ENPV or EIRR, is considered to assess project performance instead of punctual performance indicators based on baseline values.

The steps necessary to perform a risk assessment and, in turn, to estimate the probability distribution of the ENPV are discussed in section 5.4, 'Uncertainty of the social impacts of research: the role of risk analysis'. In section 5.5, 'How to present the CBA results of RDI infrastructures', the distribution functions of the CBA result indicators and the simple statistics resulting from the risk analysis are presented.

6.2 Time horizon

Some of the benefits produced by the RDI infrastructures last and even materialise beyond the operational phase of the project (i.e. after it useful technical or economic life) and, in some cases, are permanent. In principle, this phenomenon implies setting a time horizon for the analysis that is longer than the infrastructure's life cycle, or even one that is infinite.

For instance, when a major telescope detects a new phenomenon in the sky, an accelerator observes a new type of particle, or a therapy to cure a cancer pathology is discovered, such knowledge exists forever and is transmitted generation after generation to

[97] A B/C ratio that exceeds one indicates that the project has a positive ENPV. Indeed, the B/C ratio uses the same information as the ENPV but presents it in a slightly different manner. However, the B/C ratio can be misleading when ranking projects, which are mutually exclusive alternatives because they do not account for the scale of the project (Boadway, 2006). Conversely, the NPV is also an appropriate criterion for choosing from a group of comparable projects. In this case, the objective is to select the project that maximises the NPV (de Rus, 2010).

[98] The need to adopt formal risk-based approaches to address an uncertain future is widely recognised by the literature (Pouliquen, 1970; Reutlinger, 1970; Clarke and Low, 1993; and Savvides, 1994).

future researchers without any clear endpoint. Thus, the accumulation of knowledge has a longer – possibly almost infinite – time horizon than the period of operation of the infrastructure[99]. However, an infinite time horizon leads to a paradoxical result because any large investment cost spread throughout a finite range of years is less than the sum of any small benefit spread over an infinite time horizon, whatever the non-strictly positive social discount rate.

Another reason for the adoption of a finite reference period is related to the obsolescence process of both the equipment and the value of knowledge over time. For example, this obsolescence is observable in the trend of citations of both scientific publications and patents. In retrospect, indeed, we know that past discoveries and inventions have lost some of their scientific/technological value and have been surpassed by current knowledge and technology.

As a result, for the RDI infrastructure to be able to demonstrate a positive economic return, assuming a long but finite time horizon seems reasonable, such as one that ranges from 20 to 30 years depending on the nature of the project. Generally, the end year can be set by considering the useful life of the main equipment. Specifically, the following criterion applies: when extraordinary maintenance of the main equipment or machine became so frequent and expensive that replacing them with new ones is more convenient, the equipment/machine has arrived at the end of its life. Additionally, considerations in terms of advancements in the scientific field and subsequent possible obsolescence of the technology used should be considered.

To take into account the fact that some assets and benefits from the end of the period of analysis still have an expected value, a residual value should be computed. Similar to the residual value of a fixed asset whose economic life is not yet completely exhausted – which reflects the remaining service potential[100] – the project effects that last beyond the reference time horizon should be included in the last year of the analysis as a residual value.

Box 18. Residual value

The residual value of a project reflects the remaining value of the investment at the end of its project lifetime. Since an investment involves many fixed assets, the residual value should be calculated through its asset components, i.e. by calculating a residual value for each infrastructure item and then summing them (Jones et al. 2013). The following different calculation methods exist.

- The European Commission (2014) recommends calculating residual value as the residual market value of fixed capital as if the capital was sold at the end of the time horizon, in other words, the discounted value of all net future revenues.
- In practice, the residual value of fixed assets is frequently calculated as the present value of expected net cash flows during the years of the economic life outside the reference period, i.e. the considered time horizon, if the economic life exceeds the project lifetime period.
- Another method consists of estimating the amount that an entity would currently obtain from the disposal of the assets net the estimated cost of disposal.
- A simple and commonly used method is the straight-line depreciation method, in which the residual value is equal to the non-depreciated amount of the asset, and the concept of remaining service life (RSL) is exploited. The formula is: residual value = [(RSL/total service life) * initial capital cost].

In the RDI context, in which some benefits may continue after the infrastructure's decommissioning (such as technological spillovers on firms and human capital effects on former students and young researchers), the calculation of the residual value should not only rely on the remaining value of the fixed capital but also on the discounted value of the benefit that exceeds the project's time horizon. Indeed, even if such effects occur beyond the CBA's time horizon, they have been generated as a result of the infrastructure.

6.3 The social discount rate

The long time span of effects influences the decision over the most appropriate social discount rate[101] to adopt to discount economic flows to reflect the social view on how benefits and costs are to be valued against present ones. In most CBA practices, a constant social discount rate is used, which implies an exponential discounting process of the project's flows. In other words, benefits occurring far in the future are discounted more than the costs of investments that, instead, typically occur in the initial years of the time horizon. This greater discounting could lead to negative project performance indicators and to the decision of not implementing the project, disregarding the concept that the same project may bring significant benefits to the welfare of future generations.

[99] Possible similarities can be found in environmental economics and, in particular, the economics of climate change, in which a few hundred years are frequently considered to evaluate the impact of a policy intervention. For example, the Stern Review (HM Treasury, 2006) sets a time horizon of 200 years. Another 'extreme' example is suggested by Boardman et al. (2006). The latter, to stress that the benefits of some projects may continue to flow from many years even if the project is finished from an engineering or administrative perspective, mentions the case of roads originally laid down by the Romans more than eighteen centuries ago and that are still the basis of contemporary motorways.

[100] The residual value should not be taken into account unless the asset is actually liquidated in the last year of the analysis.

[101] The social discount rate reflects the inter-temporal opportunity cost of capital for the entire society and is used in the economic analysis to discount flows. Different approaches exist in the literature to estimate the social discount rate. The most popular approaches are the social rate of return on private investments and the social rate of time preferences.

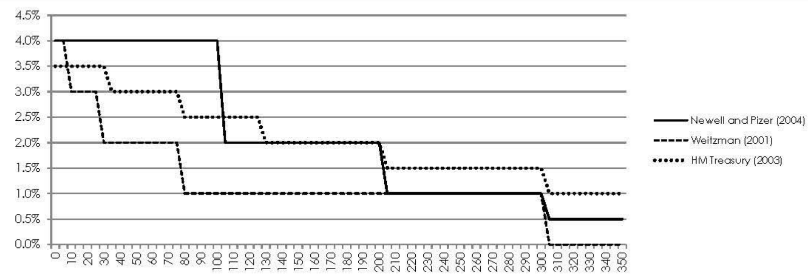
One possible way to address the issue raised by a constant rate is to adopt a sufficiently low discount rate. One example is in the Stern Review on the Economics of Climate Change (HM Treasury, 2006). See The social discount rate in the Stern Review of Climate Change.

Box 19. The social discount rate in the Stern Review of Climate Change

The Stern Review adopts the Social Rate of Time Preference (SRTP) approach and assumes a near-zero pure time preference (equal to 0.1%), representing the possibility of extinction of the human race. The elasticity of the marginal utility of consumption is set to 1 and the expected rate of future per capita growth is assumed equal to 1.3% per annum, in accordance with historical data. When these values are entered into the SRTP formula[102], they result in a rate of 1.4% in real terms. However, the social discount rate estimated by the Stern Review has been criticised for being too low. In fact, it does not consider the impatience component, which implies that a greater weight be attached to the present generation. Moreover, to be consistent with the saving rates, the elasticity of the marginal utility of consumption should be higher (Nordhaus, 2007; Weitzman, 2007; Dasgupta, 2007 and 2008).

Another possibility suggested in the literature is to use a declining discount rate, following a hyperbolic discounting function (Laibson, 1977) and characterised by relatively high discount rates in the short term and relatively low rates over long horizons. Figure 9 exhibits some declining social discount rate patterns proposed in the economic literature.

Figure 9. Some declining social discount rates



Source: Authors based on cited sources.

With respect to empirical estimation, significant variations in the social discount rate adopted by different governments exist depending on the estimation method used and the specific underlying parameters (see Table 14). However, when assessing the RDI infrastructure, a further aspect that should be considered when choosing the most suitable social discount rate is that, in most instances, the rate cannot be country specific because the project benefits spread relatively quickly and globally – for instance, consider the technological spillovers and knowledge outputs.

[102] The SRTP formula is based on a formula obtained from the Ramsey growth model. SRTP = p + ε* g, where p is the pure time preference, ε is the elasticity of the marginal utility of consumption, and g is the expected growth rate of per capita consumption.

Table 14. Social discount rate adopted in selected countries

Country	Social discount rate	Estimation approach	Source
Australia	8%, with sensitivity test over the range 3-10%	Social rate of return on private investments	Harrison (2010)
Canada	8%, with sensitivity test over the range 3-10%	Social rate of return on private investments	Treasury Board Secretary Canada (2007)
China	For short and medium term projects: 8%. For long term projects: 8%	Weighted average	Zhuang et al. (2007)
European Union	3% for cohesion countries and 5% for other member states	Social Rate of Time Preference	European Commission (2014)
France	4% (declining after 30 years)	Social Rate of Time Preference	Quinet (2007)
Germany	3%	Social Rate of Time Preference	Florio (2006)
Italy	5%	Social Rate of Time Preference	Florio (2006)
Netherland	4%	Social rate of return on private investments	Florio (2006)
Slovak republic	5%	Social Rate of Time Preference	OECD (2007)
UK	3.5% (declining after 30 years)	Social Rate of Time Preference	HM Treasury (2003)
USA (office of management and budget)	7%	Social rate of return on private investments	Zhuang et al. (2007)

Source: Authors adapted from Florio (2014).

6.4 Uncertainty of the social impact of research: the role of risk analysis

To account for the uncertainty and risk that characterises the future, the risk assessment is generally required as the last step of the project's ex-ante appraisal (see *inter alia* Zerbe and Dively, 1994; de Rus, 2010; Florio, 2014).

In general, deviations from predictions can be related to a number of different causes. A broad distinction exists between endogenous (e.g. errors incurred ex ante or during project implementation) and exogenous (e.g. changes to the project context caused by an unpredictable event) sources of risks (Florio, 2014). Whereas the latter is hardly predictable and, thus, outside the control of the project manager and evaluator, the former can be identified and minimised ex ante. According to Flyvbjerg *et al.* (2003), three broad categories of explanations exist for endogenous errors: technical, psychological, and political-economic[103]. Also available is the intrinsic uncertainty associated with the forecast of future trends. All of these factors can potentially affect the appraisal exercise to provide the decision maker with a more or less biased outlook of the expected project outcomes (Flyvbjerg, 2013). Even if some of the mentioned causes of deviation from predictions, such as accidents, are unpredictable, the sources of uncertainty can at least be identified to enable the parties to be ready to react and able to manage them if they appear. Instead, when a probability distribution function reflecting the degree of risk can be assigned to an event, doing so can be embedded in a risk assessment.

However, for the RDI infrastructure, the uncertainty of the CBA results can be even greater than that for other traditional infrastructures. This result is affected by the following range of factors.

- Frequently, RDI infrastructures are designed to be unique and breakthrough compared with the past; therefore, no references are available or suitable enough to forecast future trends.

[103] Technical explanations refer to errors and pitfalls in forecasting techniques; psychological explanations refer to planning fallacy and optimism bias (i.e. the tendency ex ante to overestimate benefits and underestimate costs and timing for a project); political-economic explanations refer to the fact that project promoters may deliberately overestimate benefits and underestimate costs when forecasting project outcomes.

- The experiments and tests are subject to some probability of success or failure (see Figure 6). Actually, research, development, and innovation involve the generation of new knowledge, and the probability of success depends on many factors, not all of which are under the direct control of RDI projects' promoters or are easy to be forecasted.
- Experiments and tests could generate discoveries that produce positive impacts that cannot be estimated when the funding decision is made.
- Only some experiments and tests are planned from the beginning and a new set of services and possible uses of the RDI infrastructure could arise during the RDI life cycle. This potentiality makes a RDI infrastructure intrinsically different from a standard infrastructure that, at least to a certain extent, is designed from the beginning to deliver a relatively well-defined set of services.

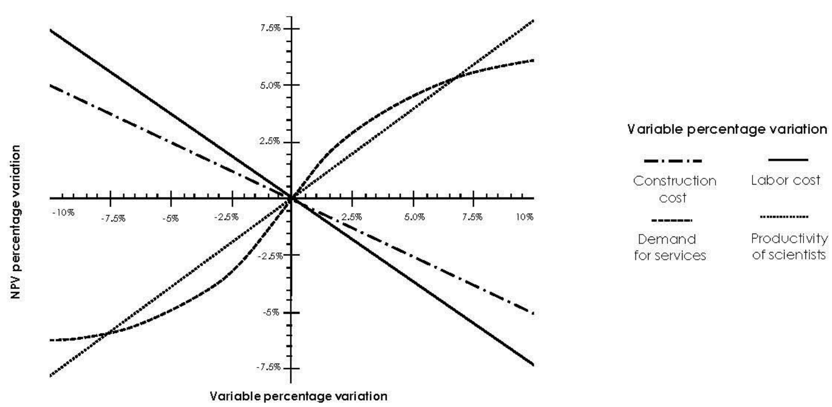
The two latter points describe inherently unpredictable effects. They have a quasi-option value (see *Boxes 15 and 16*); however, because forecasting the probability of occurrence and magnitude of this quasi-option value is usually impossible, the convenient working hypothesis is simply to assume that their values are non-negative and skip them. Conversely, the uncertainty characterising the first situation can be defined as measurable because it can be embedded into a stochastic model through probability distributions and, thus, tested using a risk assessment.

The set of procedures for overall risk assessment is traditionally split into three steps.

The first step is a sensitivity analysis. The impact of each variable entering the analysis on the predefined outcome measure (such as ENPV or the EIRR) is assessed by changing each 'best guess' value in absolute terms or by arbitrary percentages, one by one. Having then set the criterion for deciding whether the variation in the output is sufficiently large, the most critical variables for the CBA can be identified. The European Commission (2014) suggested focusing on a neighbourhood of 1% around the 'best guess'. In other words, a 1% change in the value of the independent inputs of the CBA is assessed, and the variables leading to a greater than 1% change in the outcome measure are considered critical. However, a good practice is to consider a range of percentage variations around the best estimate on a continuum scale ranging from, e.g. –10% to +10% (Florio, 2014). This practice allows detecting the non-linear and non-symmetric effects of the variables on the project outcome (see *Figure 10*). A specific category of the sensitivity test is the scenario analysis (see

- Scenario analysis on this matter).

Figure 10. Sensitivity analysis plot



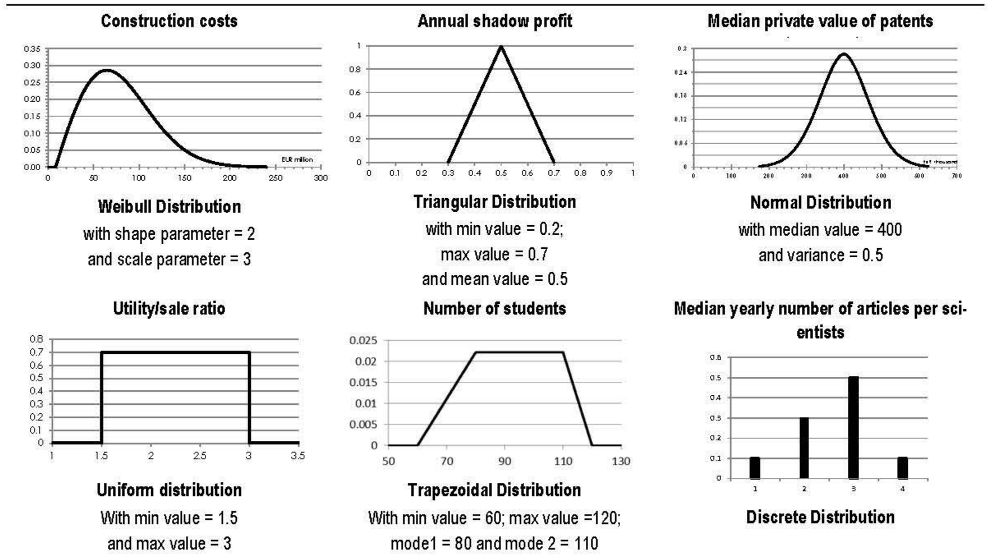
Source: Authors

Box 20. Scenario analysis

Scenario analysis, also called 'what-if' analysis (Vose, 2008), is a specific form of sensitivity test. Whereas the influence of each independent variable on project performance is tested separately under standard sensitivity analysis, scenario analysis studies the combined impact of sets of values assumed by the critical variables[104]. In particular, combinations of 'optimistic' and 'pessimistic' values of a group of variables could be useful to build extreme scenarios and calculate the extreme limit of the project performance indicators. To define the optimistic and pessimistic scenarios, the extreme values defined by each critical variable's distributional probability should be used.

- Second, a range of variations and a specific probability distribution function are assigned to each identified critical variable. Probability distributions are highly dependent on the specific type of project under evaluation and may be determined from various sources of information, including experimental data, distributions found in the literature and adopted in projects similar to the one under assessment, and time-series or other types of historical data (Vose, 2008). When insufficient data exist to construct probability distributions, the range and likelihood of possible values rest on project promoter and evaluator judgments. Some exemplificative probability distributions are provided in Figure 11.

Figure 11. Example of probability distributions



Source: Authors

- Third, the project's riskiness is assessed using the Monte Carlo simulation method[105], which allows estimations of the integral corresponding to the probability distribution function of the project performance indicator of interest (e.g. ENPV). By extracting one value of each critical variable from the respective cumulative distribution function and plugging it into the CBA model, the associated NPV is computed. This process, if repeated over a large number of iterations, leads to the probability distribution of the project ENPV. In other words, through the law of large numbers, which implies the convergence of the ENPV empirical distribution to its 'true' counterparts, the CBA result can be considered in probabilistic terms and the minimum, maximum, mean, and standard deviation values of the NPV can be computed.

Table 15 contains a list of typical risks affecting RDI projects and the relative variables that are likely to be critical and should be tested in the sensitivity analysis. As a final remark, it is worth mentioning that, in addition to the riskiness attached to variables entering the social CBA on either the cost or the benefit side, the results of the CBA model for RDI infrastructures could be strongly influenced by two important parameters: the time horizon of the analysis and the social discount rate. Our indication is to assess the var-

[104] Defined as critical through the standard sensitivity analysis.

[105] For a review, see, for instance, Robert and Casella (2004) and Balcombe and Smith (2011).

iation in the CBA results also subject to different assumptions on the length of the time horizon and of the chosen discount rate and discounting function (exponential, hyperbolic, or others).

Table 15. Typical risks and critical variables in RDI infrastructure projects

Stage	Risk	Critical variables
Design and construction	• Inadequate site selection • Inadequate design cost estimates • Project cost overruns • Delays in completing the project design/in construction/during installation of equipment • Accidents	• Number of years necessary for the construction of the infrastructure • Investment costs
Operation	• Delays in making the equipment fully and reliably running • Unexpected environmental externalities/accidents • Insufficient production of research results • Lack of academic staff/researchers • Demand of students/young researchers different than predicted • Demand of industrial users different than predicted • Interest in general public different than predicted	• Expected incremental shadow profit; • Number of patents expected to be registered over the project time horizon; • Economic value of patents; • Survival rate of spin-offs/start-ups; • Number of stakeholders benefitting from technological spillovers; • Expected incremental profit earned by suppliers; • Number of scientific publications expected to be produced over the project time horizon; • Estimate of the unit economic value of scientific publications; • Average number of citations received by scientific publications; • Number of young researchers and students benefiting from human capital development; • Expected incremental salary obtained by students as a result of human capital development over their professional career; • Size of targeted population; • Avoided cost or WTP for reduced environmental or health risk; • Forecast of the success rate of the project; • Estimated WTP of visitors; • Value of environmental impacts.
Financial	• Inadequate estimate of operating costs • Inadequate estimate of financial revenues • Insufficient success in obtaining research funding • Loss of existing clients/users due to competition from another RDI infrastructure	• Operating costs • Licence revenues gained from patents' commercialisation • Revenues from services sold to third parties • Revenues from target population using the research outputs • Revenues from outreach activities

Source: Authors adapted from European Commission (2014).

6.5 How to present the CBA results of RDI infrastructures

As noted, project performance may be assessed in probabilistic terms using a Monte Carlo simulation that approximates the probability distribution functions of the ENPV and the EIRR and their cumulative distribution functions, whose shapes are reported in Box 21. Whereas the probability distribution function summarises the likelihood of occurrence of all outcome values randomly extracted during the Monte Carlo simulation, the cumulative distribution function returns the probability that the outcome is equal to or smaller than any given value in the range of the variation in the considered performance indicator[106]. Thus, the latter can be directly exploited to observe the cumulated probability that corresponds to some feasibility threshold. Namely:

- When considering the ENPV, the interest is on the probability (Pr) that the ENPV is equal to or smaller than zero. Hence, if Pr $\{ENPV \leq 0\} \approx 0$, then the project can be judged as socially desirable.
- When considering the EIRR, the interest is on the probability that the EIRR on the probability is smaller than the adopted social discount rate (r). Hence, if Pr $\{EIRR \leq r\} \approx 0$, then the project can be judged as socially desirable.

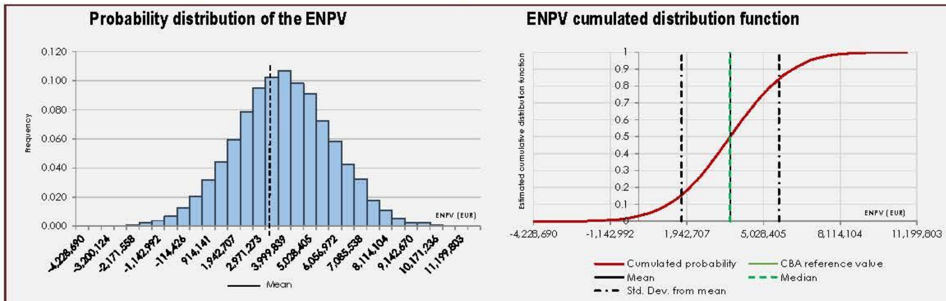
Additional relevant information on the project performance is provided by various summary statistics of the estimated PDF of the outcome values, i.e. the ENPV and the EIRR. In particular:

- The range of variations consists of the window of values – from minimum to maximum – within which the ENPV and the EIRR vary. The range of variations provides a picture of the project's variability. In general, a project with a narrower range of variability in its performance indicators is preferable, *ceteris paribus*.
- The mean value is the estimate of the expected value of the ENPV and the EIRR, and is interpreted as the outcome expected to occur over a large number of potential project realisations. Thus, the expected mean values provide an immediately readable synthesis of the indicators of the most likely discounted social value of the project.[107]
- The standard deviation consists of the variation around the mean values of the ENPV and the EIRR. In general, no rule exists for interpreting the standard deviation as 'high' or 'low' in absolute terms. However, this synthesis indicator can provide useful information if compared with those of similar type projects.[108]

All of these elements form the CBA results of the RDI infrastructures and are used to judge the investment's social worthiness and riskiness, along with other criteria.

[106] To further explore this topic, see chapter 9 in De Rus (2010) and chapter 8 in Florio (2014).
[107] The ENPV calculated in a deterministic model, i.e. as the outcomes of the best guess value of variables, do not exactly coincide with the expected value of the ENPV, i.e. the mean ENPV resulting from a Monte Carlo simulation process.
[108] A useful synthetic ratio is the coefficient of variation, i.e. the ratio of standard deviation to the mean, which is a dimensionless number and thus comparable between projects.

Box 21. Probability distributions of the ENPV and synthesis statistics

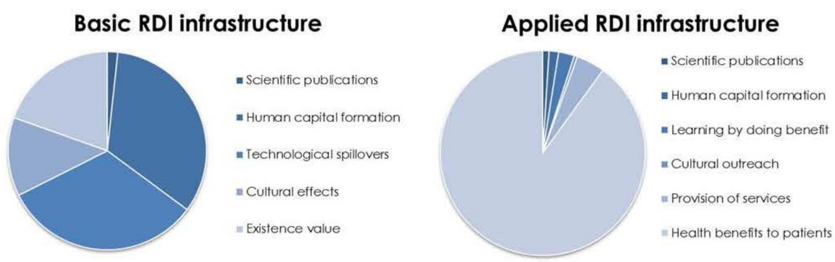


Estimated parameters of the ENPV probability distribution

Mean	3,694,224
Median	3,685,960
Standard deviation	1,959,403
Minimum	-4,228,690
Maximum	11,199,803

Finally, for communication purposes, presenting CBA results in a disaggregated manner could be useful, such as by breaking down each discounted benefit, by distinguishing between the expected value of use and non-use benefits, or according to a group of beneficiaries (firms, students, the general public). The use of pie charts could assist in presenting the various breakdown of benefits arising from the infrastructure in a reader-friendly manner.

Figure 12. Example of distributions of the discounted benefits for two hypothetical research infrastructures



Source: Authors based on analysis of case studies.

6.6 Wider economic impacts

RDI infrastructure investments are often financed within broader territorial development strategies (regional or national). As a matter of fact, RDI facilities may become a crucial element in the development path of a territory, as witnessed by experiences of high-tech clusters developed also thanks to the relationship with research facilities located in the same region[109]. In such cases, relevant economic impacts in the form of employment or technological spillover effect on existing or newly created SMEs in the region are included in the CBA as described in the previous sections. Additional wider benefits, for example in terms of contribution to regional GDP, are not accounted in quantitative terms within the CBA model as their inclusion within the socio-economic assessment is still subject to a lot of discussion.[110]

Typically, these impacts include agglomeration economies, multiplier effects, labour supply impacts, impact on competition, or changes in the value of land or houses. In a RDI context, there may be demonstration effects on the general population, particularly

[109] See for example OECD (2009).

[110] The discussion on wider economic impacts is particularly developed in the transport sector. See inter alia Venables (2007), Betancor et al. (2013).

the young, about the role of science and technology. For instance, the proximity of universities to a RDI project may convince a larger share of students to achieve a degree in sciences and this, in turn, could be somewhat correlated to the long-term regional growth rate. Also, an RDI facility which attracts high quality personnel, possibly from other regions or abroad, may contribute to opening the cultural horizon of the local society. This in turn can contribute to an increase in local social capital and in some particularly beneficial cases, even to the improvement of the overall quality of institutions.

All these impacts are appealing. Nevertheless, there are two main problems regarding their inclusion within the CBA (Jorge-Calderón, 2014): firstly, many of these effects are already accounted for within the direct effects heading. In this respect, it is worth noting that wider economic impacts in terms of labour are already accounted for by means of shadow wages (see section 3.3). Secondly, in many cases these effects do not incorporate a counterfactual comparison, and hence would not be measuring the incremental relevant benefits. Therefore, such type of impacts within a CBA framework shall not be included in the quantitative analysis, but better described in qualitative terms.

The territorial dimension of an RDI infrastructure is an important element for the decision taker, which must be carefully considered in the option analysis[111]. In fact, the availability of relevant know-how and human capital on the territory may have important effects in terms of costs on the RDI construction and operation.

[111] The selection of infrastructure project should always result from a throughout analysis of the alternative project options. The criteria to be considered when assessing each option are discussed in in the new Guide for the CBA of investment (European Commission, 2014). They concern, for example, the technological solutions employed and the choice between building a brand new facility rather than improving an already existing one. The localisation of the project can also be a relevant selection criterion. Actually, the territorial dimension of human, technological, physical and production capital endowment can be decisive to determine the project localisation, which in turn affects the potential for the project to promote regional development.

7. Concluding remarks

This paper contributes to the literature on the ex-ante appraisal of large-scale, capital intensive RDI infrastructures. Specifically, it presents the main findings and lessons learned from a three-year research on how to advance social CBA methods for RDI facilities. The approach proposed is intended to complement and not substitute for other evaluation methods, including peer review assessments or road mapping.

Our approach can be summarised as follows. RDI facilities are, after all, infrastructures. As such, the CBA principles and rules for the appraisal of infrastructure projects should be exploited and adapted as best as possible. In line with this goal, our model recurs to: 1) shadow prices to capture social benefits beyond the market or financial value; 2) a counterfactual scenario to ensure that all costs and benefits are estimated in incremental terms; 3) discounting to convert any past and future value in their present equivalent; and 4) a consistent identification of social benefits with respect to CBA theory.

At the same time, given some features of RDI infrastructures, such as the intangible nature of certain benefits and the uncertainty associated with achieving the results, a tailored approach to these specificities has been devised. There are three novelties in our approach. First, we identify the core types of beneficiaries in terms of the standard economic agents: firms, consumers, employees, taxpayers, and we present the specificities of the RDI arena in this perspective (such as the coincidence of producers and consumers for certain types of research).

A second novelty of our approach consists of breaking down the intertemporal benefits into two broad classes: use and non-use benefits. The former refers to benefits held by different categories of infrastructure users, such as scientists, firms, students, and general public visitors. The latter benefit denotes the social value for the discovery potential of the RDI infrastructure regardless of its actual or future use. In an heuristic perspective this break-down has the advantage of avoiding the confusion that has often delayed until know the application of CBA to RDI infrastructure projects.

A third significant feature of our approach is the stochastic nature of the CBA model. Indeed, all critical variables entering the model are expressed in terms of expected values instead of punctual values. This approach circumvents another issue that has until now hindered the application of CBA to the RDI infrastructure, i.e. the unpredictability of the social value of knowledge.

Hence, the approach presented in this paper is consistent with the main principles of CBA, but also novel and heuristic. Although many of the ideas that we use are firmly rooted in CBA tradition in different fields, their application to the RDI context is in its infancy. Therefore, we hope that this discussion paper encourages further applications and testing to fine tune and expand the current methodologies and techniques. In particular, forecasting technological spillovers and human capital effects would need econometric 'treatment' techniques; the estimation of the social value of discoveries using contingent valuation methods needs to be tested by relying on both existing and future facilities; forecasting media impact of outreach is another interesting topic to be studied in greater detail. Further research is also necessary to investigate issues that go beyond what we have been able to address until now. Such possible issues include for example assessments of RDI projects' broader economic impacts (including in the territorial perspective), the possible use of real option analysis to value the flexibility and risk of RDI infrastructures[112], advances in risk analysis to consider correlations of stochastic variables, use of Bayesian networks in the study of social preferences. Exploring the use of CBA in such a new field of application will reveal other challenging issues.

[112] As suggested by the EIB (2013). See footnote 17.

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