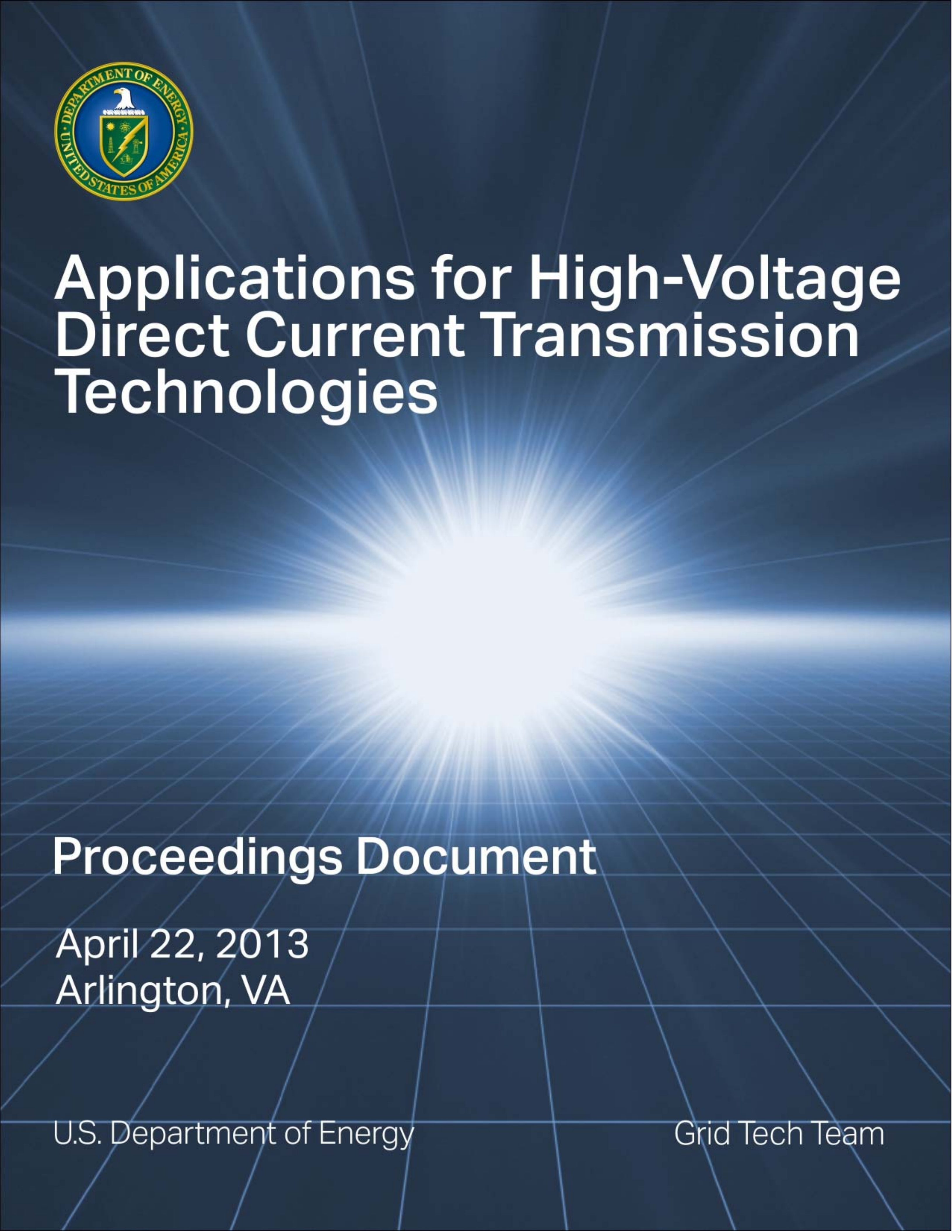

Applications for High-Voltage Direct Current Transmission Technologies

Proceedings Document

April 22, 2013
Arlington, VA

U.S. Department of Energy

Grid Tech Team

Introduction

The advantages of high-voltage direct current (HVDC) transmission over conventional high-voltage alternating current (HVAC) technologies are well established for long-distance, point-to-point power transfers.[1] HVDC has also been deployed in subterranean and submarine applications where overhead lines are impractical and where HVAC has higher electrical losses. HVDC also has the unique capability to connect asynchronous grids; this capability may have more value in the future with greater numbers of microgrids. HVDC technologies can also provide extremely rapid stability control, power flow control, and the ability to segment parts of the power system—all of which can enhance the grid's flexibility, reliability, and resilience.

Although HVDC transmission is a fairly mature technology, recent technological improvements have expanded its capabilities and applicability for addressing grid challenges. New commercial applications and deployment opportunities may open up as conditions change in the U.S. electric power sector. Changes include evolving generation mixes and load profiles, increasing customer expectations for reliability and resilience, and persistent challenges to siting new transmission. Applications such as submarine HVDC networks can open new possibilities for power management and provide a practical way to access large amounts of off-shore wind.

Currently, advanced HVDC transmission projects are being proposed, designed, and built around the world, especially in Europe and Asia. Thus far, HVDC deployment activity within the United States has been limited, with about 20 transmission facilities. Figure 1 depicts the more than 35 HVDC transmission facilities across North America.

---

[1] http://smartgrid.ieee.org/resources/interviews/368-ieee-smart-grid-experts-roundup-ac-vs-dc-power, *accessed October 19, 2015*

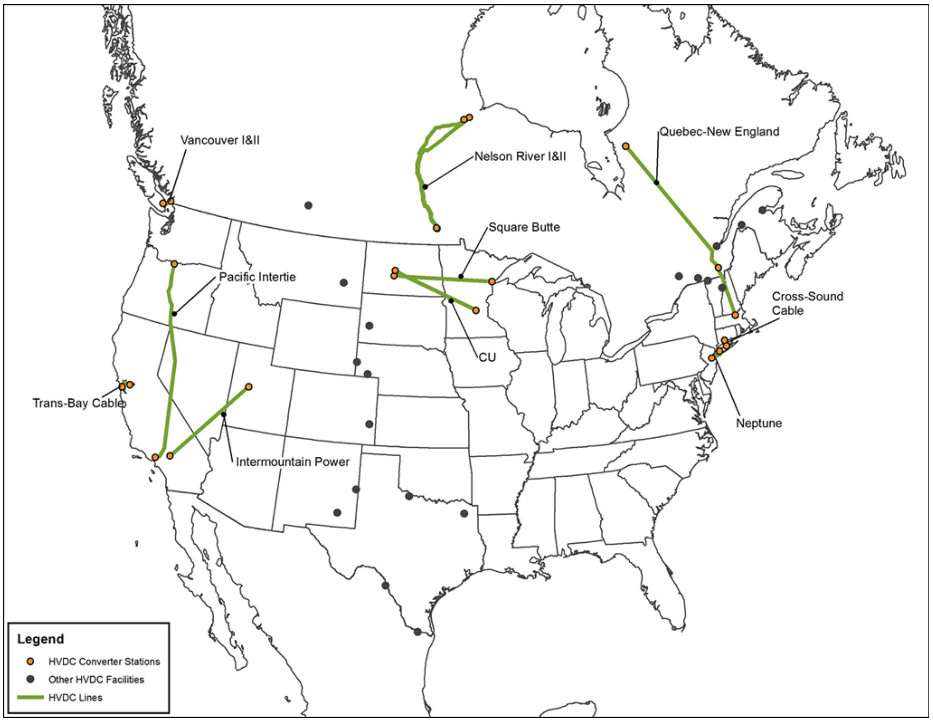

Figure 1: North American HVDC Deployment

By assessing the current landscape of technologies and identifying potential ways to address barriers to deployment, the U.S. Department of Energy (DOE) examined opportunities to improve prospects for HVDC technologies.

Workshop Process

On April 22, 2013, DOE's Grid Tech Team (GTT) held a one-day workshop to develop a better understanding of HVDC transmission technologies and their application in the North American electric grid. In the morning, industry stakeholders showcased the state of the art for HVDC transmission technologies through a series of presentations and case studies.[2] In the afternoon, workshop participants discussed various technical and institutional barriers to greater deployment, as well as potential opportunities to address those barriers. The morning session began with a keynote presentation to baseline participant understanding of HVDC technologies. The presenter discussed trade-offs between HVDC and HVAC transmission options and provided insights into the merits and limitations of line-commuted converter (LCC) systems and voltage-source converter (VSC) systems. The speaker also compared HVDC deployment opportunities across developing countries, Europe, and the United States.

The keynote address was followed by two panels: State of HVDC Technologies and U.S. Project Case Studies. In the first panel, three HVDC technology vendors presented the state of the art and highlighted

---

[2] http://energy.gov/oe/downloads/hvdc-workshop-april-22-2013

recent international projects where their products were deployed. In the second panel, representatives of four companies presented HVDC projects in their portfolios and discussed various aspects of those projects:

- The transmission challenge that led to the proposed HVDC solution
- The basic project configuration and technology choice
- The reasoning behind the decision
- Key challenges encountered and lessons learned

The various presentations highlighted the breadth of applications for HVDC technologies, such as increasing power delivery with constrained right-of-ways (ROWs), delivering renewable power over long distances, providing access to off-shore wind generators, and sharing power between asynchronous grids. The panels were followed by a moderated panel discussion and a question-and-answer period.

The afternoon session comprised two facilitated group discussions. The first discussion focused on key technical, institutional, and regulatory challenges to implementing cost-effective applications of HVDC within the next five to ten years. During the second discussion, participants proposed actions to address the identified challenges and examined the respective roles of government and industry in leading those actions.

Discussion Summary

Keynote and Panels

The choice between using HVDC or HVAC is usually justified by economics, i.e., decision makers look at costs versus benefits. For example, system stability can be much better with HVDC, and more power can be transferred over the same ROW than HVAC. In general, HVDC is more cost-competitive than HVAC for power transmission over 600 miles aboveground or 30 miles underground/underwater. However, recent technical advances have decreased the breakeven point to 300–350 miles for aboveground transmission. Other decision factors include geographic considerations, such as whether the transmission lines should go over a mountain or undersea. Typically, transmission owners have no preconceived preferences for overhead versus underground lines. Other benefits of using HVDC that may not be considered include the ability to provide frequency regulation, forcing ordered power into an area, limiting fault currents, and providing black start capabilities.

Applications of HVDC technologies include water crossings, asynchronous interconnections (back-to-back), bulk power transfers including access to remote renewables (point-to-point), transmission in areas with severely restricted ROWs, and HVDC networked grids (multi-terminal). These various applications provide unique benefits but also present distinct challenges. For example, HVDC can be used to deliver power into dense urban centers, but converter station placement and visual impact regulations in those areas can be difficult. Another example is the use of HVDC to connect wind power in high-capacity factor regions to load centers. Employing HVDC has the potential benefit of minimizing the correlation of wind generation within a region, but the application is constrained to balancing areas that can absorb the increased variability. More unique applications include accessing off-shore wind, which has geo-electric appeal, and connecting the three US interconnections to help balance real and reactive power flows between the systems.

Currently, two viable power electronic device options exist, leading to two families of HVDC converters. LCCs, based on thryristor technology, have the inherent ability to clear faults. VSCs, based on insulated gate bipolar transistor (IGBT) technology, have superior controllability. VSCs are currently more expensive and have higher losses than LCCs and require fault management, but they have the potential for more diverse applications such as connection to weak systems (in which the short circuit ratio is less than 3) and multi-terminal HVDC. LCCs are more mature and can provide high power transfer capabilities but require a connection to a strong system or some form of reactive power compensation (volt–amperes reactive [VARs]), especially with undergrounding. The traditional view is that LCCs can be utilized only in a robust grid; however, some workshop participants stated that the limitation is not valid since a synchronous condenser can be used. Another alternative is to use a capacitor-commutated converter configuration. LCCs have been the workhorse of the industry since the 1980s and are readily used for bulk power transfers. VSCs have been deployed only within the past decade, but the technology is slowly increasing power ratings and overcoming bottlenecks.[3]

Despite the recent advances in HVDC converter technologies, many technology gaps, such as control algorithms and HVDC breakers (or dynamic breaking resistors), need to be addressed for multi-terminal applications. Two approaches for HVDC breakers are being pursued: a full semiconductor version and a hybrid semiconductor–mechanical version. The current state of HVDC breaker development is similar to the development pathway of HVAC breakers; losses remain the key issue. Steady progress on HVDC breakers has been made, with increasing capabilities for interrupting larger currents in shorter timeframes (e.g., 3000 A in 2.5 ms); a product with commercial potential would be expected to break in 5 ms. Once developed, HVDC breakers will still have to compete with HVAC breaker options with half-bridge configurations, full-bridge converters, or other electronic fault suppression techniques. Another challenge is that HVDC breakers need to be designed for the requirements of a specific application. For example, the maximum voltage generated by the breaker must be low enough to conform to the insulation coordination of the system.

Technology hurdles may not be a significant issue to greater deployment. Losses in power electronic devices, especially with VSC technology, affect only the business proposition of using HVDC. Research on converters, switches, and configurations is currently ongoing, and such projects have made steady progress in reducing losses and lowering prices. Controllability has also improved tremendously, but concerns remain about the impact of lightning strikes on overhead lines and insulation. Offshore applications also face their own challenges with corrosive environments, but the deployment experiences in Europe and the oil platform industry's maturity mitigate some of these concerns.

The global state of HVDC deployments can be categorized in three groups: developing countries, Europe, and the United States. In developing countries such as Brazil, China, and India, HVDC transmission is being built primarily to transfer large quantities of power over long distances. In Europe, the limited

---

[3] http://www05.abb.com/global/scot/scot221.nsf/veritydisplay/1f9325bfc027ca6dc1256fda004c8cbb/$file/HVDC%20Light%20and%20development%20of%20VSC.pdf, *accessed October 19, 2015*

opportunity to build transmission lines aboveground has resulted in HVDC deployments primarily focused on underground or submarine applications. The United States has a need for both long-distance and underground applications but has substantial siting challenges.

In Europe, several initiatives and projects support HVDC deployments, e.g., DESERTEC, Friends of the SuperGrid, North Seas Countries Offshore Grid Initiative, and the Council on Large Electric Systems (CIGRE). Participating in some of these initiatives would allow the United States to learn best practices from Europe. Lessons learned from developing countries are less applicable. Technology-based best practices can be transferred, but the regulatory environments are decidedly different. Furthermore, other countries typically have a single entity that has jurisdiction over an entire project, whereas the United States has a state-by-state approach for transmission, which presents additional challenges.

In fact, the biggest challenge in application of HVDC is regulatory issues. For example, FERC Order 1000 requires the allocation of costs of new transmission projects to beneficiaries. However, there are single-driver projects, multi-driver projects, projects to meet public policy requirements, regional projects, and non-regional projects. Identifying beneficiaries is difficult since some projects have regional benefits that are not explicitly considered. For instance, AWS Truepower performed a net load analysis to estimate the increase in operating reserves needed to integrate 3500 MW of wind energy into the Tennessee Valley Authority (TVA) and surrounding systems.[4] For TVA alone, the integration would require an increment of 383 MW of operating reserves, but if TVA, Southern, Duke, and Entergy join forces, TVA's need drops to only 127 MW. There are also economic benefits from reducing load payments and production costs (addressing congestion to lower locational marginal pricing). Because of regulatory and cost allocation concerns, the customer rate base is hard to develop, making it difficult to finance HVDC projects. A national infrastructure development bank in legislation could help address financing concerns.

Another non-technical challenge to overcome is the inherent resistance to using HVDC in system planning. A lack of knowledge about the technology's full capabilities impedes its full exploitation. One issue is that private sector organizations developing HVDC technologies have little to no representation in the groups conducting planning. By connecting with utilities, the private sector could identify and resolve the unknowns in planning, accelerating technology deployment. However, system planners have valid concerns. Large injections of power can create contingency issues, and utilities need to consider possible North American Electric Reliability Corporation (NERC) criteria violations during planning.

Another concept for planning is consideration of a national HVDC overlay, which has a unique set of challenges. Currently, there is no effective way to study the issue and incumbent entities tend to restrict the development of a national overlay; any work done reinforces the status quo. One critical question is who would be responsible for conducting global planning. The scope of a utility generally does not include looking at projects with broad system benefits due to issues with protection of interests within their service territories and cost allocation. Limited optimism exists for global plans since there are many

---

[4] AWS Truepower. "Load Coincidence Study for the Integration of Wind into Tennessee Valley Authority via the Plains and Eastern Clean Line" (Albany, NY: June 25, 2010). http://www.cleanlineenergy.com/sites/cleanline/media/resources/AWSTruePower.pdf.

interests at stake and politics in play; the general sentiment appears that planning will happen regionally at best. However, it is recognized that technological advancements can be a real driver for change.

Overall, it is hard to determine a general pricing for HVDC since every project is unique; the as-built costs including regulatory delays, choice of technology, fluctuations in material costs, and other factors must be considered. However, PJM's Transmission Expansion Advisory Committee provides a good source for HVDC project costs. A potential benefit of utilizing HVDC underground transmission is that undergrounding could provide owners the ability to avoid many issues related to community resistance (i.e., "not in my backyard" [NIMBY]), possibly offsetting total costs.[5]

HVDC is a great enabling technology, but decision makers must be careful that the technology is not a solution searching for a problem. Cost–benefit analysis is key to decision making, and there are non-transmission alternatives to solve many problems. For example, in the Eastern Interconnection Planning Collaborative (EIPC), ISO New England found that HVDC was not a cost-effective alternative for some of the problems they face.

Key Challenges and Opportunities

Workshop participants identified several key challenges and opportunities that would benefit from DOE's involvement. These can be grouped into several categories:

- Valuation and analyses
- Tools, models, and data
- Education, outreach, and workforce
- Research, development, and standardization
- Demonstrations and test beds
- Policies, regulations, and cost allocation

The remainder of this section of the workshop report summarizes the workshop discussion within these categories. Each section ends with a list of opportunities for DOE action.

Valuation and Analyses

Since implementation of HVDC is ultimately based on cost–benefit analyses, it is important to get the value of HVDC correct. Developers in Brazil, China, and India did not pick the high-cost solution; they incorporated broader benefits into their analyses. Most U.S. developers are merchant developers; the main goal of implementation is not necessarily for reliability. Although implementation offers a range of opportunities, the economics may not support the project with current valuation methodologies. Other

---

[5] http://www.pjm.com/committees-and-groups/committees/teac.aspx

transmission assets and alternative solutions should be considered and evaluated before going directly to HVDC.

It is important to be able to quantify benefits in the planning stages of a project; however, some benefits may be difficult to quantify. There are social benefits that are not taken into account and have direct implications for cost allocation. For example, the deployment of HVDC links can help prevent widespread blackouts, but this benefit is not valued. HVDC also provides some flexibility that cannot be achieved with implementing additional alternating current (AC) lines. There is also a tendency to focus on “real” costs, but opportunity costs should also be factored. For example, when deciding between overhead versus underground transmission, the time required for overhead siting (AC lines can take up to 14 years) and the associated costs should be factored in valuation. Proper planning time horizons are important as well; projects can take 10 years to build and will address needs 20–30 years after project initiation. For some large transmission projects, a risk-based analysis approach may be useful.

Although HVDC has been studied for some time, every project is different and requires customization. There needs to be an overarching view of the various applications and modes where HVDC can serve as a solution. The technology provides benefits such as provision of reactive power, black start capabilities, flexibility, and controllability; these benefits should be valued and factored into decision making along with maintenance and lifecycle costs. Contingency planning is also a concern; planners need to be careful when locating termination and source points since losing those large injections of power can be a problem. Other impacts to consider include environmental factors, system stresses, harmonic issues (which will require filters), cascading effects (N-1 contingency analysis can be more complicated with converters), and the risk associated with LCC’s such as multiple commutation failures.

Ultimately, valuation and analyses should look at the full system instead of each individual component (e.g., cables, converters, circuit breakers); HVDC needs to be studied in a comprehensive and integrated manner. An established methodology is needed since there is no clear means of quantifying system benefits. Geographic differences also affect valuation. For example, markets are flow-based in the east and contract path-based in the west. One can extend benefit calculation to include domestic job creation from demonstration, manufacturing, and technology development. DOE should organize a group for this effort to ensure objectivity and credibility.

Proper analyses can inform potential markets; several scenarios should be explored. Understanding the bottlenecks in the U.S. grid will help identify future capacity expansion needs and required upgrades, as well as providing improved situational understanding of infrastructure options. The grid is evolving and those changes will have a range of impacts. For example, electric vehicle deployment will affect future grid transmission needs and increases in offshore wind generation can create a new market for HVDC. The concept of developing a national backbone with associated national benefits is worth investigating. Analyses also need to explore transmission corridors and HVDC’s likely and potential impacts. Exploring the comparison between alternating and direct current (AC and DC) to understand the “spread” of benefits across regions (with geographic differences) would also be worthwhile. Studying the long-term value of undergrounding transmission and/or a study of the entire grid to determine the market for HVDC could be an initial step.

Opportunities for DOE include the following:

- Establish a group to analyze a national strategy for HVDC
- Assemble a group to develop a framework to assess benefits and value of projects
- Develop guidelines/methods for what should be included, and determine how HVDC—or more broadly, transmission—should be valued; including quantification of societal benefits
- Develop and publish guidelines in partnership with the Institute of Electrical and Electronics Engineers (IEEE)
- Publish a study showing the cost-effectiveness/benefits of underground HVDC transmission
- Conduct impact analyses, and study how complex interactions are modeled and what tools are used
- Support systems analysis with information sharing

Tools, Models, and Data

Tools are needed to support the planning of transmission upgrades and expansions, whether HVDC or other options are used. Models and tools are available but their application and sophistication is limited. Currently, no capability exists that can model HVDC as a full system, such as studying a DC overlay in the United States. There are also no tools to study control of real and reactive power, in steady state as well as dynamic analyses, especially for VSC technology. Real-time simulation capabilities are also needed.

Understanding the strength of the system and how it handles stresses is important. There are concerns with maintaining stability when large amounts of power leave the system, and the implications regarding reliability. For example, there is a need to understand how a system with HVDC can sustain an unplanned outage. There is also a need to study the optimal way of controlling a system with multiple DC lines and the associated number of converters. The additional controllability can be beneficial but can be challenging for operations. With phase shifters already in existence, as well as other control technologies, there may be too many levers and uncoordinated changes. As for DC fault management, a 500 kV fault can cause a significant voltage dip; managing these faults and understanding the broader system impacts should also be considered.

The grid is complicated and tools that can conduct comprehensive, complex analyses are needed. Technical challenges associated with HVDC implementation depend on specific applications, and tools are needed to study the technology from a system perspective, including dynamics, harmonics, control interactions, and contingencies. The industry also needs to ensure that planning tools can accommodate the proper time horizon, given the long duration of projects. Analysis tools that can conduct risk-based planning would be useful and would provide consistency with current planning approaches. Dynamic tools and analyses can also help to identify and define value.

In addition to tools, underlying models are also very important. Power system simulator for engineering (PSSE) model libraries currently exist but may not be useful for looking at certain system factors. Additionally, older infrastructure (1980s) presents modeling gaps; the models may be outdated, incomplete, hard to find, or non-existent. Accurate models are needed for other system components but their availability is limited. The application of models that are developed is not entirely clear; they are not plug-and-play with existing tools. Consistency to ensure model interoperability as well as broader support for modeling would be helpful to the industry.

It would also be useful to conduct a general assessment of HVDC models to determine whether they are broadly applicable and to identify how many products are commercial. HVDC provides the ability to control the volt/VAR ratio; modeling would help to capitalize on this ability. These high-speed control options should be incorporated and the dynamics evaluated. Current models need to factor in the capabilities provided by HVDC, as tools are not currently available to assess these scenarios. HVDC will also be used to access wind power, which will necessitate new models.

There are currently PSCAD models that converge, but bridging and linking to PSSE models remains an issue. Not only will PSLF-type models be needed, but also EMTP-type analyses. A coordinated set of models, including generator and torsional models, is required to study the harmonics and interactions of HVDC with the grid. Appropriate models will be needed to study the HVDC systems and lines, as well as the individual devices that make up the converters. Developing these models can be a joint collaborative effort between many stakeholders (industry, academia, government). DOE's computation capabilities could be utilized to model the entire grid, resulting in a dynamic model of the grid from macro to micro scale that could be accessed from a laptop.

Furthermore, data on performance and costs are needed for proper modeling, analysis, and planning of HVDC technologies. Preliminary costs for implementation, operations and maintenance, life cycle, etc. are needed for effective comparison with other technologies. Comparisons of reliability characteristics are also very important. More detailed data is needed for these systems, including information about cost per mile, cost over time, and how numbers change as technology advances or equipment ages. DC cable costs also need to be authenticated; costs need validation but information from other industries can be leveraged. Despite the importance of data, the unique characteristics of individual projects make it difficult to get useful cost and performance information.

Opportunities for DOE include the following:

- Fund new models, and produce analysis tools with a systematic, collaborative effort
- Identify the landscape of HVDC tools and models
- Help transition available models into commercial software
- Develop a simulation tool that can assess impacts on reliability
- Support work by the Electric Power Research Institute (EPRI) and others for modeling
- Support data collection for models and costs

Education, Outreach, and Workforce

An education issue exists for industry, transmission planners, and other stakeholders. There are different levels of understanding, as well as misconceptions about new and advanced technologies. General lack of understanding, adequate tools, and education about HVDC creates an atmosphere of fear, exacerbated by insufficient examples of successful projects. There is a need to increase the common understanding of HVDC, to deprogram the industry, to move beyond focusing on AC solutions, and to expand thinking about how DC can be integrated and used. Tutorials or webinars tailored to different stakeholders, from engineering students to executives, should be developed. Efforts will have to be customized for individual stakeholder groups: public utility commissions, engineers, academics, and industry executives.

Sharing of best practices can also help with education and prevent reinventing the wheel on issues encountered with HVDC implementation in different states and regions. Additionally, knowledge that something has been done before (in a similar environment) will encourage further consideration of that technology or process. A website with information about capabilities and possibilities would be helpful. HVDC has been studied and deployed for some time so there should be sufficient cases from which to draw. Benefits and risks associated with various parameters, such as performance under lightning strikes with overhead lines and the use of VSC technology should also be included. To address these issues, DOE should facilitate information sharing and leverage resources, research, and lessons learned across the government. The Department of Defense has relevant experience with electric ships, and there are international lessons-learned as well. Additionally, DOE provides a degree of neutrality not always perceived with a supplier's website.

Furthermore, there are various efforts to assess HVDC, such as the DOE-conducted transmission congestion studies, DOE-funded HVDC studies in Hawaii, a State Department-funded study in Puerto Rico, and exploration of corridor utilization by the Western Electricity Coordinating Council (WECC) and the Eastern Interconnection States' Planning Council (EISPC). These studies and efforts should be coordinated and leveraged with an eye toward minimizing redundancy. Assessing and tabulating what has been done and what is on-going would help prevent duplication and add value. There is also a need for documentation of realistic and pragmatic case studies. Project information should be presented in a structured framework that is accessible to diverse users. Project tracking should be done with an overarching view to highlight issues that may come up in other projects.

Another aspect of education deals with the future workforce; industry needs a young workforce with the appropriate training and skills. However, no professors currently teach HVDC; it is not included in academic curricula. Universities are currently hiring for smart grid technologies, so HVDC should be folded into an expanded scope. Furthermore, students should be engaged before college through earlier exposure to power systems engineering and HVDC. A government campaign could also increase interest in engineering; HVDC's environmental benefits could help with marketing. Based on IEEE publications, Europe boasts many PhDs and authors in relevant fields, so the potential to grow interest should exist in the United States.

The availability of sufficient funding resources needs to be considered, as it helps drive academic research and student training. The American Recovery and Reinvestment Act (ARRA) provided $100 million for education but was not a sustained commitment. A National Science Foundation/industry joint fellowship program could be implemented to ramp up the next generation of HVDC experts. A joint DOE/vendor fund for universities and education programs would also provide needed financial assistance. Another facet is attracting students to these opportunities. Decent salaries incentivize students to pursue a career but job placement concerns remain. DOE can leverage national laboratories as regional centers to provide experience for students; internships are another mechanism to pursue.

Opportunities for DOE include the following:

- Leverage GEARED and other efforts from other agencies[6]
- Develop and maintain a website for information on HVDC, including capabilities, best practices, and case studies
- Gather information from industry and international sources
- Develop tutorials
- Develop use cases of comparable efforts
- Develop educational tools for academics
- Assess both international and domestic projects

Research, Development, and Standardization

Despite being considered a mature technology, HVDC still presents several technical challenges. New hardware development, controls, and advanced concepts can help address these challenges. Specific R&D needs and issues identified are summarized in the table below:

Technologies	**Issues**
Converters	• Converter losses are high; wide-bandgap materials and other new materials may help to reduce losses • IGBT devices have limited power ratings; higher power ratings desired • Power devices have limited availability; they are only accessible through large-device manufacturers and are costly • VSC technology requires more investigation • Multi-terminal configurations are need for DC networks • DC-to-DC conversions are not direct; DC-to-DC step-up transformers could improve controllability
Controls	• New controllers are needed to manage power flows, leveraging the high-speeding of the technology to support grid stabilization o It must accommodate possible communication failures

---

[6] http://www.irecusa.org/workforce-education/grid-engineering-for-renewable-energy-deployment-geared, *accessed October 19, 2015*

	• Coordinating controls with the broader electric power system in current and future scenarios o Off-shore wind farms with a DC backbone o Master/slave considerations and hierarchical control • Concerns with fault management o Restart times needed for the entire system o Segmentation of the grid with HVDC; explore the concept of graceful degradation
Breakers	• DC breakers are needed to manage faults in a DC networked system; while developments are promising, they may not be available for at least 10 years • For an LCC point-to-point system, the converter itself is the best breaker currently available to deal with overhead line faults; unfortunately, LCC is not very suitable for multi-terminal systems • For VSC technology, a full-bridge can suffice and be more economic as a breaker but it will depend on the application
Sensing and Diagnostics	• Taking HVDC off-line (planned or unplanned) will disrupt a large amount of power flows, possibly leading to other issues; Early awareness for preventative maintenance is necessary to mitigate risks.
Cables	• Cables are a critical component of HVDC systems; Commensurate advances are needed including the application of new materials

Some of basic components and technologies in the table are used in other sectors; advances made in these fields and by different entities (e.g., the Department of Defense) could be leveraged to address the issues. Another significant challenge is that AC systems and technologies have good interoperability; various pieces of hardware from different vendors can be integrated. This is not the case with DC systems where all hardware needs to be from the same manufacturer. Standardization could improve interoperability and reduce costs in the near-term and into the future, especially when considering maintenance and turnover.

Opportunities for DOE include the following:

- Fund R&D for wide-bandgap semiconductors and other materials
- Support public–private partnerships to help accelerate R&D and ultimately drive down costs
- Support standardization for components
- Help develop control concepts for multi-terminal applications
- Support HVDC breaker research and an associated pilot

Demonstrations and Test Beds

Grid operators who are responsible for reliability need to trust in HVDC technology and understand how to manage it. However, this requires an extended study of new devices, good study methodologies, and ultimately a track record, as it is difficult to put trust in unproven technology. Simulations are helpful but are not a substitute for live demonstration. HVDC technologies are complex; they are not plug-and-play and can lead to unexpected control interactions. Understanding these potential system impacts will be needed to support their integration. For example, in the event of a component failure, AC technologies have an on and off state, whereas DC technologies have many in-between states. Demonstration and testing of new technologies in combination with control strategies will also be very important.

Expanded use of HVDC will likely stress operations and the specifics must be understood. The new technology must be properly controlled and monitored. Data for models and simulations must also be validated and verified. Field tests of the technologies would help overcome concern about deployments and improve the accuracy of data. Existence of a test facility for multi-terminal DC development is particularly desirable. It would also be good to ensure that VSC technologies will works in applications with off-shore generation. The number of project cycles for new technologies and concepts is not yet sufficient, so government assistance with initial demonstrations is important.

Partnerships are the most efficient means of investigation to address these challenges. For example, to research controllers, industry needs the testing infrastructure and vendors can supply the components and systems. Additionally, resources at national laboratories could also be leveraged for demonstration projects. One example is the Energy Systems Integration Facility (ESIF) at National Renewable Energy Laboratory (NREL) which could serve as a test bed to run various scenarios. Preliminary work can be done at national laboratories, but it is important to remember that actual field tests will have different results. Power marketing administrations should also be leveraged for large-scale demonstrations or deployments. Another capability that is beneficial is a real-time digital simulator (RTDS), which enables testing of hardware in the loop and of various controllers. The RTDS can help develop and verify system and control models.

The true costs of first demonstrations or pilot projects are not known; there are many uncertainties and instanced where things can go wrong. Unfortunately, this presents a “Catch-22” scenario as businesses do not want to invest in the demonstrations that are needed to inform business models that spur greater investments. The federal government should partner with project developers to help assess the means of cost reduction, technology development, and showing how the technology works. Tax incentives or loan guarantees may help make demonstrations more accessible.

DOE-funded demonstrations should be top-down projects at the national level; some demonstration projects are better led by federal entities than by public utilities. Federal support underscores a project’s national significance and can be used strategically to break down barriers. Pilots are usually too small; utilities need scaled-up demonstrations to make an economic impact. Projects that support public policy objectives, such as power purchase agreements and contracts, should have state and regional support and participation. Island territories can be good candidates for HVDC demonstrations.

Demonstrations that examine unique value propositions are also important. One example is the conversion of AC lines to DC. If the capacity on existing AC lines are limited because of system constraints, then conversion to DC lines could be considered. Such a project would be able to demonstrate and quantify various benefits such as the time and resources saved (e.g., increasing transmission capacity in limited ROWs where the actual conductors are reused). Because of customer resistance to transmission expansion, issues with NIMBY, converting AC to DC can provide significant value. Another potential project is installing synchrophasor technology with an HVDC system. Such a demonstration would show how HVDC can improve AC system controls. Additional benefits include the verification of AC grid models and controls and supporting the development of new models.

Opportunities for DOE include the following:

- Fund demonstration projects
- Partner with industry to scale up demonstration projects
- Provide HVDC vendors with a test facility for testing various components
- Build or leverage test beds such as at the NREL-ESIF
- Show conversion of AC to DC and benefits of undergrounding
- Become more strategic with options for demonstrations

Policies, Regulations, and Cost Allocation

Policies and regulations have a big impact on markets and cost allocation, as well as having the potential to level the playing field for new technology. Regulatory authority for transmission and wholesale electricity exists for AC systems; the used and useful requirement for regulators can be limiting HVDC deployment. Additionally, how the benefits of HVDC fit into existing markets and regulations is not clearly understood; policy innovation will be needed to support new technologies. Policies that encourage manufacturing in the United States are also important as there is a risk that HVDC will not be developed or piloted here, possibly resulting in the loss of domestic technology leadership.

There is also a need to revisit compliance standards as policies developed in the past tend to be accompanied by a good deal of inertia. The Federal Energy Regulatory Commission (FERC) can take a proactive role in reexamining laws and regulations to drive institutional changes. Historically, FERC has taken a blanket approach to policy making; however, specific situations and associated contingencies should be considered such as whether HVDC is handled on an energy basis or a capacity basis. Additionally, reliability requirements may change for a future system. For example, it is important to consider what an “N-1 contingency” would mean for HVDC and what the right metric would be.

From the deployment experience in Europe, which also faces a challenging institutional and regulatory environment, regional coordination and collaboration for planning and implementation has shown benefits. Domestically, FERC Order 1000 is meant to support regional planning and is a step in the right direction. Regional planning can help support HVDC implementation, but some aspects (e.g., the technology’s uniqueness and benefits) may not be considered. One potential scenario is a national long-distance HVDC backbone; where the grid is handled liked the federal highway systems with a sense of national responsibility. This scenario is unlikely absent a national energy policy which faces many externalities. Most likely, regional or interconnection planning will occur but the issue with siting and permitting, which are lengthy processes, will remain; interconnection queues can also be dysfunctional.

Community resistance to new projects (NIMBY) and similar issues may require government intervention, such as backstop authority of government. HVDC for accessing offshore wind will present unique siting and permitting challenges as well, and should be addressed concurrently.

Cost allocation is another important barrier, as the prevailing mindset is to implement solutions with the lowest cost rather than what is regionally optimal. According to FERC Order 1000, beneficiaries must pay development costs for projects but determination of benefits is difficult. With HVDC point-to-point transfers, determining the primary beneficiaries can be simple, but flyover concerns (i.e., lines crossing states that do not benefit) makes things more complex. In places where HVDC does not originate or terminate, the administration and calculation of these "side payments" must be incorporated in cost allocations. It is difficult to build a project where costs are imposed on others. Documents produced by WECC for engaging with stakeholders, which includes HVDC as part of the discussion, may be a resource. Public policy considerations, such as economic development and environmental concerns, can add to the complexity. Additionally, global benefits are not taken into account; a sharing mechanism could be established to cover externalities and broader beneficiaries.

Financing is a big concern for many new technologies; increased project risks lead to higher cost of capital and thus higher electricity prices. Most developers make decisions based on the internal rate of return (IRR); a high IRR for a HVDC project translates into implementation. Additionally, societal benefits of improved transmission—such as reliability, climate effects, and cleaner energy—are not presently factored into financing considerations. These intangibles should be monetized; financing mechanisms that are tied to societal benefits could encourage deployment. Additionally, changes to the Federal Power Act could also spur deployment. For example, FERC regulations could ensure a return on investment for HVDC; allow 50 percent of costs to be spread to cover regional benefits; or accelerate the write off of installed technologies to hasten adoption and implementation of new technologies.

Another issue is that it is often easier to finance smaller capital expenditures, resulting in a preference for the deployment of overhead AC lines to solve problems. The credit of the state should be behind projects that support meeting the national interest. A government fund could help pay for incremental costs between two technology choices if the more expensive choice (e.g., undergrounding vs. overhead) would be the better option to meet public policy objectives. Loan guarantees and production tax credits for transmission and distribution infrastructure can also be used to lower risks and facilitate financing.

Opportunities for DOE include the following:

- Convene a group to establish valuation criteria and cost allocation
- Help establish guidelines and educate regulators
- Work with FERC and provide technical expertise
- Evaluate reliability standards with HVDC
- Explore new markets and financing schemes
- Provide support through loan guarantees

Next Steps

Overall, there was recognition that HVDC technologies have valuable applications but face a range of challenges. A group can be formed to continue engagement with the community, identify specific technical needs, and determine means to address those needs. DOE could provide resources to initiate these types of groups (e.g., the North American Synchrophasor Initiative); however, they should ultimately become vehicles of and for the vendor/user community and are self-funded.

The GTT will take the information obtained from this workshop into consideration in the development of future DOE plans and activities. Individuals who were not able to participate at the workshop can submit comments and additional thoughts to the GTT via GridTechTeam@hq.doe.gov.

Meeting Participants

First Name	Last Name	Affiliation	Email
Ram	Adapa	EPRI	radapa@epri.com
Sam	Baldwin	DOE/EERE	Sam.Baldwin@ee.doe.gov
Venkat	Banunarayanan	DOE/EERE	Venkat.Banunarayanan@hq.doe.gov
Gil	Bindewald	DOE/OE	Gilbert.Bindewald@hq.doe.gov
Anjan	Bose	DOE/Undersecretary	Anjan.bose@hq.doe.gov
Erin	Boyd	DOE/PI	Erin.boyd@hq.doe.gov
Ralph	Braccio	Booz Allen Hamilton	braccio_ralph@bah.com
Darren	Buck	WAPA	DBuck@WAPA.GOV
Mary	Cain	FERC	mary.cain@ferc.gov
Caitlin	Callaghan	DOE/OE	Caitlin.callaghan@hq.doe.gov
Jay	Caspary	SPP	jcaspary@spp.org
Kerry	Cheung	DOE/OE	Kerry.cheung@hq.doe.gov
Rahul	Chokhawala	GE	Chokhawa@ge.com
Charlton	Clark	DOE/EERE	Charlton.Clark@ee.doe.gov
Stephen	Conant	Anbaric Transmission	sconant@anbaricpower.com
Jose	Conto	ERCOT	jconto@ercot.com
Matt	Cunningham	GE	Matt.Cunningham@ge.com
Mohamed	El-Gasseir	Atlantic Wind Connection	mme@atlanticwindconnection.com
Joe	Eto	LBNL	jheto@lbl.gov
Wayne	Galli	Clean Line Energy	wgalli@cleanlineenergy.com
Vahan	Gevorgian	NREL	vahan_gevorgian@nrel.gov
Peter	Grossman	Siemens	peter.kohnstam@siemens.com
Tim	Heidel	DOE/ARPA-E	Timothy.Heidel@Hq.Doe.Gov
Jeffrey T.	Hein	Xcel Energy	Jeffrey.T.Hein@xcelenergy.com
Nari	Hingorani	Consultant	nghingorani@sbcglobal.net
Cynthia	Hsu	DOE/OE	Cynthia.Hsu@Hq.Doe.Gov
Holmes	Hummel	DOE/Undersecretary	Holmes.Hummel@hq.doe.gov
Sasan	Jalali	FERC	sasan.jalali@ferc.gov
Ehsan	Khan	DOE/FE	Ehsan.Khan@Hq.Doe.Gov
Tom	King	ORNL	kingtjjr@ornl.gov
Neil	Kirby	Alstom	neil.kirby@alstom.com
Peter	Kohnstam	Siemens	peter.kohnstam@siemens.com
Rich	Kowalski	ISONE	rkowalski@iso-ne.com
Barry	Lawson	NRECA	barry.lawson@nreca.coop
Per-Anders	Lof	National Grid	Per-Anders.Lof@nationalgrid.com
Lucas	Lucero	BLM	llucero@blm.gov
Jack	McCall	American Superconductor	jmccall@amsc.com
Paul	McCurley	NRECA	paul.mccurley@nreca.coop
Ben	Mehraban	AEP Transmission	bmehraban@aep.com
David	Meyer	DOE/OE	David.Meyer@hq.doe.gov
Rich	Meyer	NRECA	Richard.meyer@nreca.coop
Doug	Middleton	DOE/FE	Douglas.middleton@hq.doe.gov

First Name	Last Name	Affiliation	Email
Dave	Mohre	NRECA	dave.mohre@nreca.coop
Phil	Overholt	DOE/OE	Philip.overholt@hq.doe.gov
Bill	Parks	DOE/OE	William.Parks@hq.doe.gov
Mahendra	Patel	PJM	patelm3@pjm.com
Rich	Scheer	Consultant	scheerllc@verizon.net
Pam	Silberstein	NRECA	pamela.silberstein@nreca.coop
Alex	Slocum	MIT/OSTP	slocum@mit.edu
Holly	Smith	NARUC	hsmith@naruc.org
Le	Tang	ABB	le.tang@us.abb.com
Robert J.	Thomas	Cornell	rjt1@cornell.edu
Brittany	Westlake	DOE/OE	brittany.westlake@hq.doe.gov
Cynthia	Wilson	DOE/PI	Cynthia.Wilson@hq.doe.gov
Jon	Worthington	DOE/OE	Jon.Worthington@Hq.Doe.Gov
Montee	Wynn	NRECA	montee.wynn@nreca.coop

Acronyms

A	Ampere
AC	Alternating Current
CIGRE	Council on Large Electric Systems
DC	Direct Current
DOE	U.S. Department of Energy
EIPC	Eastern Interconnection Planning Collaborative
EISPC	Eastern Interconnection States’ Planning Council
EPRI	Electric Power Research Institute
ESIF	Energy Systems Integration Facility
FERC	Federal Energy Regulatory Commission
GTT	Grid Tech Team
HVAC	High-Voltage Alternating Current
HVDC	High-Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated Gate Bipolar Transistor
IRR	Internal Rate of Return
kV	Kilovolts
LCC	Line-Commuted Converter
ms	Milliseconds
MW	Megawatts
NASPI	North American Synchrophasor Initiative
NERC	North American Electric Reliability Corporation
NIMBY	Not in My Backyard
NREL	National Renewable Energy Laboratory
PSLF	Positive Sequence Load Flow
PSSE	Power System Simulator for Engineering
ROW	Right-of-Way
RTDS	Real-Time Digital Simulator
STATCOM	Static Synchronous Compensator
TVA	Tennessee Valley Authority
U.S.	United States
VAR	Volt–Ampere Reactive
VSC	Voltage-Source Converter
WECC	Western Electricity Coordinating Council