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Transmission Innovation Symposium

Modernizing the U.S. Electrical Grid

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**Electricity Transmission
System Research and
Development:
Hardware and
Components**

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April 2021

Electricity Transmission System Research and Development: Hardware and Components

**Transforming Transmission:
Modernizing the U.S. Power Grid**

2021 White Papers

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Foreward

The foundation of the U.S. Department of Energy (DOE) Transmission Reliability research program was established 20 years ago through a series of commissioned white papers. The white papers reviewed the dramatic institutional and regulatory changes that the transmission grid was undergoing and articulated the technical challenges that those changes created. The challenges outlined in those white papers were used to formulate the initial research goals of the Transmission Reliability program.

Today, 20 years later, many of the targets set out for the program have been accomplished. At the same time, the electricity grid is undergoing a dramatic shift with the addition of substantial renewable and distributed energy resources and heightened risks from phenomena such as severe weather. These shifts pose new challenges for the transmission grid, today and into the future. As a result, now is an appropriate time to step back and review the current technical challenges facing the industry and to identify the next set of targets for DOE's transmission-related research and development (R&D) programs within the Office of Electricity's Advanced Grid Research and Development Division.

To support this process, DOE, supported by Lawrence Berkeley National Laboratory (LBNL) and Pacific Northwest National Laboratory (PNNL), has commissioned small teams of experts drawn from the national laboratories and academia to prepare a new set of foundational white papers. Each white paper reviews and assesses the challenges now facing the U.S. transmission system from the perspective of the technologies that will be required to address these challenges. The focus of the white papers is on technical issues that must be addressed now to prepare the industry for the transmission system that will be required 10-20 years in the future. A key purpose of these papers is to identify technical areas in which DOE can take a leadership role to catalyze the transition to the future grid.

The five white papers are:

- 1. U.S. Electricity Transmission System Research & Development: Grid Operations**
Lead Authors: Anjan Bose, Washington State University, and Tom Overbye, Texas A&M University
- 2. U.S. Electricity Transmission System Research & Development: Distribution Integrated with Transmission Operations**
Lead Authors: Chen Ching Liu, Virginia Polytechnic Institute and State University, and Emma Stewart, Lawrence Livermore National Laboratory
- 3. U.S. Electricity Transmission System Research & Development: Automatic Control Systems**
Lead Authors: Jeff Dagle, Pacific Northwest National Laboratory, and Dave Schoenwald, Sandia National Laboratories
- 4. U.S. Electricity Transmission System Research & Development: Hardware and Components**
Lead Authors: Christopher O'Reilley, Tom King, et al., Oak Ridge National Laboratory

5. **U.S. Electricity Transmission System Research & Development: Economic Analysis and Planning Tools**

Lead Authors: Jessica Lau, National Renewable Energy Laboratory, and Ben Hobbs, Johns Hopkins University

The white papers will be vetted publicly at a DOE symposium in spring 2021. The Transmission Innovations Symposium: Modernizing the U.S. Power Grid will feature expert panels discussing each white paper. The symposium will also invite participation and comment from a broad spectrum of stakeholders to ensure that diverse perspectives on the white papers can be heard and discussed. Proceedings will be published as a record of the discussions at the symposium.

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Acronyms and Abbreviations

AC	alternating current
AI	artificial intelligence
AM	advanced manufacturing
BaTiO ₃	barium titanate
CSAC	chip scale atomic clock
CT	current transformer
DC	direct current
DER	distributed energy resource
DLR	dynamic line rating
DOE	U.S. Department of Energy
eLoran	enhanced long-range navigation
FACTS	flexible alternating current transmission system
FCL	fault current limiter
GPS	global positioning system
HVDC	high-voltage, direct-current
kV	kilovolt
LC	Inductor-capacitor
LCC	line-commutated converter
LPT	large power transformer
MIT	Massachusetts Institute of Technology
ML	machine learning
MMC	modular multilevel converter
MTDC	multi-terminal direct current
NASA	National Aeronautics and Space Administration
PBF	powder bed fusion
PMU	phasor measurement unit
PT	potential transformer
R&D	research and development
RTU	remote terminal unit
SCADA	supervisory control and data acquisition
SiC	silicon carbide
STATCOM	static synchronous compensator
UPFC	unified power-flow controller
U.S.	United States
UTC	coordinated universal time
VSC	voltage source converter
WBG	wide bandgap
ZnO	zinc oxide

Executive Summary

Purpose and Scope

The U.S. energy delivery system faces many challenges from an evolving generation mix, aging infrastructure, integration of new technologies and legacy systems and increases in threats to energy infrastructure. This white paper focuses on transmission technology hardware and components to help ensure the reliability and resiliency of the future grid. To determine the transmission technology priority for R&D focus, we developed future scenarios and identified the technology solutions that would be essential in addressing the challenges presented in each scenario. Technologies that cut across multiple scenarios were identified as key solutions: power-flow control systems (reactive power devices, power electronic components), high-power delivery technologies (e.g., advanced conductors, high-voltage, direct-current [HVDC] systems, transformers), advanced sensors, and advanced protection systems. We present recommendations for U.S. Department of Energy (DOE) investment in research and development (R&D) to support these technologies.

Some technology areas that will be essential for the future grid are omitted from this white paper because they are being addressed elsewhere: an energy storage R&D roadmap is being addressed within the Energy Storage Grand Challenge; The cyber security R&D roadmap activities fall under the Office of Cybersecurity, Energy Security, and Emergency Response; energy management systems, advanced controls, and technology related to policies and markets are addressed in other white papers in the series to which this paper belongs.

Scenario Analysis to Determine Key Transmission Technologies

To prioritize transmission technologies for public-private partnerships and federal investment, our team analyzed multiple potential pathways that the future grid could take. We grouped those pathways into four scenarios and identified technology solutions that could address the challenges outlined in each scenario. The technology solutions that rose to the top in the largest number of scenarios were evaluated in this white paper.

The four future scenarios, which were defined to capture major trends that would have significant implications for future grid infrastructure and operations, are:

- A more distributed grid
- Increased clean energy with high penetration of variable renewable energy
- Increased load growth with re-establishment of manufacturing base
- Cyber and physical vulnerabilities and threats to the nation's grid

Table ES-1 summarizes the scenarios with a description of the nature of each, the challenges addressed within each, and potential solutions to address those challenges.

Table ES - 1. Summary of Scenarios

Scenarios	Description	Challenges	Solutions
Distributed	Numerous drivers are pushing toward a more distributed grid. As intermittent resources such as wind and solar become more common, traditional base-load plants such as coal and nuclear become less economically attractive.	<ul style="list-style-type: none"> • Integration of distributed generation • Decreased revenue for transmission system owners/decreased need for new transmission lines (i.e., change in business model) • Operating under reduced base-load conditions 	<ul style="list-style-type: none"> • Improved transmission/distribution simulation • Advanced adaptive protection schemes • Networked microgrid control schemes • Distributed power-flow devices • Advanced dynamic reactive power sources
Clean Energy	Utilities embrace decarbonization along with unprecedented policy changes that dramatically alter the generation mix.	<ul style="list-style-type: none"> • Generation location and alignment with load centers • Changes in power flow across the country • Localized reactive power issues • Grid flexibility response (inertia, voltage, frequency, and load/generation response) 	<ul style="list-style-type: none"> • Power electronic technologies for power-flow control • Advanced conductor and underground systems • Long-distance energy transfer
Industry Boom	Overall electricity consumption increases substantially with a major return of our nation's manufacturing base along with major electrification across sectors including transportation.	<ul style="list-style-type: none"> • Challenges in mid- to long-term transmission planning due to the uncertainties of manufacturing growth • Difficulties for load prediction and dispatch/operation due to intermittent load patterns of future mass manufacturing • Exhausted transmission capacity • Correlated load behaviors over wide geographic areas • Challenges for reactive power compensation and related regulations from low-power-factor (inductive) loads 	<ul style="list-style-type: none"> • Advanced load estimation and prediction technologies • Transmission line uprating technologies (e.g., high-temperature conducting, high-emissivity coating for increasing transmission capacity in relatively short period of time) • Advanced dynamic rating of transmission lines and transformers to improve the use rate of existing lines • Advanced reactive power compensation to accommodate low-power-factor loads
Cyber and Physical Vulnerabilities and Threats	As the national interconnected electricity grid becomes increasingly dependent on computers and data sharing, providing significant benefits for utilities, customers, and communities, it also becomes more vulnerable to both physical and cyber threats. Defenses for all types of critical infrastructure control systems, including water, gas, and transportation, must improve just to keep pace [1] [2].	<ul style="list-style-type: none"> • Cost of hardening the infrastructure to prevent attacks • Utilities seeking ways to cost-effectively address risks without "gold-plating" the system 	<ul style="list-style-type: none"> • Sensor installation for increased visibility on both operational technology and information technology systems • Unmanned aerial vehicle technology that could assist in restoration after extreme events • Technologies, including mobile transformers, to increase restoration services • Hardening the infrastructure using novel materials for grid components (e.g., advanced manufacturing)

Several key technologies consistently emerged from our analysis that addressed the conditions of these extreme scenarios. Our recommendations for future R&D investment are centered around these key technologies:

- **Power-flow control devices:** Transmission-scale reactive power devices, low-cost hybrid systems and energy storage, power electronic building blocks for multiple applications such as flexible alternating current transmission system (FACTS) devices and solid-state transformers
- **High-power delivery systems to transmit over long distances:** Ultra-conductive systems, smart materials (constructed using advanced manufacturing techniques), transformers, wireless power transfer, superconductivity
- **Advanced sensors:** High-fidelity sensors, asset monitoring (non-destructive evaluation, drone survey of lines), and alternative timing
- **Advanced protection systems:** Model-driven adaptive protection systems, negative sequence source and alignment to advanced sensor and communication technologies

Previous Work on Identifying Technologies for Research and Development

Many changes that are already under way increase the grid's options for providing necessary services but also potentially create instability. These include changes in generating mix; growth in DER; and proliferation of electric vehicles, smart buildings, and other distributed energy resources. These changes make it necessary to continually re-evaluate future bulk power system needs. DOE and other organizations have previously evaluated the state of the grid and identified research, development, and demonstration (RD&D) focus areas. Previous evaluations include the following publications:

- Grid 2030 – A National Vision for Electricity's Second Hundred Years (DOE Office of Electricity 2003)
- National Electric Delivery Technology Roadmap (DOE Office of Electricity 2004)
- Grid of the Future Challenges and Opportunities (MIT 2011)
- Quadrennial Technology Review (DOE 2015)
- The Future of Electric Power in the United States (National Academies 2021)

APPENDIX A summarizes the 2003, 2011, and 2015 reports listed above.

Table ES-2 summarizes technology recommendations from the 2004, 2011, and 2015 reports listed above. Many of the technology areas and recommendations have not changed dramatically since those documents were published. Although there have been advances, improving reliability and performance of these technologies while reducing costs (to improve market adoption) remain the biggest challenges. As described throughout this white paper, there is close alignment among the R&D recommended in previous reports and the recommendations in this report, specifically in the areas of power electronics, conductors, protection systems, and sensors. The most recent National Academies report also

highlights power electronics (inverters, direct-current transmission) and advanced grid protection as key technologies [3].

Table ES - 2. Summary of Previous R&D Recommendations

2004 Roadmap	2011 MIT Report	2015 QTR
Advanced conductors	Energy management systems integrating phasor measurement units	Control systems
High-temperature superconductors	Advanced control schemes	Advanced transformers
Electricity storage	Flexible alternating current transmission systems	Power-flow controllers
Distributed intelligence and smart controls	Information and communication	Protection equipment
Power electronics		Advanced cables and conductors

MIT = Massachusetts Institute of Technology; QTR = Quadrennial Technology Review

Technology Area Recommendations

From a technology perspective, the two most transformational elements of grid modernization will be controlling power flow and developing ubiquitous energy storage systems. As previously mentioned, energy storage is not highlighted in this white paper because it is the focus of DOE's Energy Storage Grand Challenge Initiative. Therefore, in this paper, power electronics and the associated building blocks are discussed as the game-changing technology for the future grid. These solutions will take decades to adopt, and further research is needed to reduce cost and improve reliability of these technologies. Regarding reliability and longevity, existing equipment and grid components in the field have lasted for decades. Present-day solid-state devices do not have the same long lifetimes.

The four areas where we believe that, in the near term, federal investment can make a difference, are:

- Improving the reliability and longevity of power electronics and reducing their cost
- Improving ampacity across the system through advanced conductors, next-generation components such as transformers, and hardening the infrastructure utilizing novel advanced materials and manufacturing technologies
- Increasing observability through a balance of high-fidelity sensors and low-cost monitoring devices
- Creating overall protection and relay systems using smart technologies/inverters

These four recommended technology areas are described briefly in the subsections below.

Power-Flow Control Devices

Power-flow control on the grid is critical to maintain basic operations, improve infrastructure utilization, ensure power quality, relieve power congestion, increase stability margin, and avoid power outages. On the transmission grid, adequate, optimal power-flow control has never been an easy problem to tackle because of challenges including complex grid topologies, continuously varying loads, renewables integration, and the difficulty of storing electricity.

In recent years, renewable energy and energy storage technologies have continued to mature and achieve market acceptance with the result that they have experienced exponential drops in cost. This has led to growing deployment of these technologies and a shift in generation from centralized systems to distributed energy resources. This shift poses a key future challenge as large generators, which have previously met system energy needs and provided stability, are being replaced with significant volumes of smaller hierarchal systems (even large renewable plants consist of couplings of hundreds of power electronic systems into a single plant). In the past, these smaller systems only represented a small percentage of overall system capacity and could be integrated into the grid without significant oversight. However, as their numbers and capacity grow, these systems must be reliable, efficient, and subject to increased coordination to ensure a robust power supply.

Power electronic systems are key in this effort. With proper planning and design, power electronic systems can offer the grid significant flexibility and rapid response. In addition, the renewable energy sources being added to the grid today lack the controllability needed to ensure sustained reliability. Further advancements are needed in high- and medium-voltage direct current applications. Increased penetration of power electronics on the grid is taking place through development of high-power drives (for example, in Type-3 or 4 wind turbines, industrial drives), high-voltage direct current (HVDC) systems, flexible alternating current transmission systems (FACTS), energy storage systems, inverter-based renewables like solar and wind, electric vehicle chargers, and other technologies. Ongoing research and development in new power electronic technologies will further increase penetration levels. These technologies include, but are limited to, solid-state power substations, extreme fast charging, solid-state transformers, and multi-port power electronics that integrate multiple sources/loads.

If power electronics interfaces are standardized so that they can span several applications, this would significantly improve system metrics of reliability, resiliency, power quality, security, economics, and efficiency. Adoption of standardized power electronic building blocks for different grid applications and realizing a coordinated control architecture for these building blocks could provide significant benefits, including:

- Enhanced resiliency, reliability of interconnecting microgrids through electrical and communication connectivity.
- Enhancement of microgrid resiliency considering cyber physical threats for building block approach and universal controller

- Improvements in modularity, maintainability, scalability for future expansion, and standardization for both power and control for rapid recovery and reduced downtime
- Reduction in balance of system (BOS) cost with standardization of the interfaces and interconnects
- Reduction of operation & maintenance (O&M) costs with advanced features like online health monitoring, cyber physical security

Power-flow control applications usually require large capital investment and a long R&D cycle. Therefore, we recommend that DOE support begin as soon as possible for three major R&D areas, shown in Table ES-3, that address existing and emerging power-flow control challenges for the future grid.

Table ES - 3. Power-Flow Control Devices R&D Recommendations

R&D Technology Area	Recommended R&D	R&D timeline
FACTS-based power flow control devices	<ul style="list-style-type: none"> • Accelerate maturation of advanced FACTS-based devices and emerging low-cost devices. Reduce cost and improve reliability. Facilitate field demonstrations and commercial applications of advanced FACTS-based devices, such as unified power-flow controllers, to help R&D of these technologies iterate and evolve. • Develop capabilities for testing emerging power-flow control technologies in a lab environment that closely resembles field conditions. Testing FACTS-based devices on the actual power grid is often impossible, so testbeds are needed to speed evolution of these technologies. • Iron core– based fault current limiters (FCLs) can relieve the fault conditions in the grid. The integrated use of FCLs with power-flow control devices can help relax the fault condition related design requirements of the power-flow control devices, and thus lower their costs and improve the overall reliability. 	<ul style="list-style-type: none"> • Near term (1-5 years) because the R&D cycle for FACTS technologies is long, and test facilities are needed to validate these emerging technologies.
Embedded HVDC systems	<ul style="list-style-type: none"> • Promote field demonstrations. The multi-terminal voltage source converter-HVDC system has great potential in the future grid, but for industry alone to take the technology to the next level of development and transition to widely available commercial applications could be infeasible. Field demonstrations are key for rapidly developing embedded HVDC technology. • Research to enable hybrid direct-current (DC) circuit breakers. Mechanical circuit breakers with current injection are a mature, cost-efficient technology. Pure solid-state breakers operate rapidly but limitations include cost and interruption capabilities. HVDC applications can become viable with breakthroughs in semiconductor current and voltage capabilities. Hybrid concepts will be the most promising in the near future because of their balanced performance in regard to operation speed, conduction loss, and interruption capability. • Enable alternating current (AC) to DC conversion. Studies have shown the technical and economic benefits of this technology 	<ul style="list-style-type: none"> • Near term (1-5 years) because field demonstrations and commercial applications of embedded HVDC will aid development and widespread deployment of this technology. Application of this technology in U.S. has lagged behind the rate of adoption worldwide.

R&D Technology Area	Recommended R&D	R&D timeline
	and potential wider relevance than previously thought. However, this technology has not drawn enough attention from policy makers.	
Power electronic building blocks for multiple applications	<ul style="list-style-type: none"> • Power stage subsystem: <ul style="list-style-type: none"> ○ Develop modular multi-level converter-based voltage-source converters ○ Support fundamental materials advances (e.g., magnetics, dielectrics) and manufacturing into components (e.g., transformers, capacitors) ○ Develop high-voltage (20+ kilovolt) wide band-gap (WBG) semiconductor devices for thermal management • Control and protection subsystem: <ul style="list-style-type: none"> ○ Develop system protection for WBG semiconductor devices and higher-voltage (e.g., >1 kilovolt) DC systems ○ Develop controllers, sensors, and auxiliary power supplies that require innovation to support a greater use of WBG semiconductor devices • Thermal management: <ul style="list-style-type: none"> ○ Develop new materials, more compact mechanical components, tighter integration with passives and packaging, and understanding of broader system interactions ○ Develop packaging for WBG semiconductor devices because of their high-frequency, high-temperature, and high-voltage operation 	<ul style="list-style-type: none"> • Near term (1-5 years)

R&D = research & development; FACTS = flexible alternating current transmission system; FCL = fault current limiter; HVDC = high-voltage direct current; DC = direct current; WBG = wide bandgap

High-Power Delivery for Improved Resilience and Reliability

A large portion of transmission lines in the United States were constructed more than 60 years ago, and many of them are operating well beyond their design service life. Most of them are based on 1950s technology and were neither engineered to meet today's demand nor to survive severe weather events. As electric power demand increases, more cables and conductors will be needed to increase grid capacity and interconnectivity.

Modernization and expansion of the electricity grid will require a comprehensive national vision based on consensus among the many stakeholders, along with planning to decide how the nation will deliver a significant proportion of its electricity from renewables.

Although the technologies needed to modernize and to expand the grid transmission system are largely available now, further RD&D is needed to reduce the cost of advanced technologies for high-power transmission that will enable improvements in the efficiency, durability, reliability, and resiliency of the future grid, resulting in significant economic and security benefits.

There is some urgency to making these RD&D investments now because of the length of the development cycle for many materials-based technologies. In addition, substantial cost savings could be realized by deploying new technologies concurrently—that is, expanding and modernizing the grid simultaneously. DOE has a unique role to play in sponsoring the aforementioned RD&D activities, particularly to minimize the risk of developing technologies for the risk-averse electric utility industry.

Table ES-4 summarizes our R&D recommendations for high-power delivery technologies and identifies materials and manufacturing R&D opportunities to improve the efficiency, durability, reliability, and resiliency of the electricity grid.

Table ES - 4. High-Power Delivery for Improved Resilience and Reliability R&D Recommendations

R&D Technology Area	Recommended R&D	R&D timeline
Electrical conductors	<ul style="list-style-type: none"> • Accelerate development of alloys with improved electrical and mechanical properties, using integrated computational materials science & engineering approach • Modify surface of metallic conductors to improve their oxidation and corrosion resistance while preserving low interfacial electrical resistance between conductors and connectors • Optimize engineering of interfaces between matrix and carbon nanotubes to minimize electron scattering and losses in metallic matrix composites; optimize design of metallic matrix composites by determining the distribution of sizes of carbon nanotubes and the structure (e.g., single-wall vs. multi-wall), aspect ratio, concentration, and orientation that will maximize structural and electrical properties • Develop carbon-based conductors, with emphasis on obtaining meso-scale structures that exhibit the inherent physical and mechanical properties of nano-phased materials • Develop processes for manufacturing connectors for integrating cables into electrical systems 	<ul style="list-style-type: none"> • Near term (1-5 years), based on the Energy Information Administration (EIA) Annual Energy Outlook 2020 and the number of miles of high-voltage transmission lines that will reach end of useful life in the next 10 to 20 years
Electrical insulators	<ul style="list-style-type: none"> • Support discovery of polymeric materials that exhibit high dielectric breakdown strength and high environmental durability. Efforts should also focus on investigating the effect of adding nanoparticles of SiC,* BaTiO₃* and ZnO* to polymer matrix composites because these additions can reduce the impact caused by space charge. Specific areas of investigation: determining the role of nanoparticle size distribution, concentration, and dispersion; the nature of the interface between a nanoparticle and polymeric matrix; and the resistance of the composite to moisture and temperature • Perform multi-physics simulations to determine the response of HVDC cables to the simultaneous application of thermal and electromagnetic fields, structural loads, and environmental effects (e.g., wind, rain, snow); could be coupled with topology optimization techniques to identify geometrical features that could mitigate the effect of space charge accumulation 	<ul style="list-style-type: none"> • Near term (1-5 years), based on the EIA Annual Energy Outlook 2020 and the number of miles of high-voltage transmission lines that will reach end of useful life in the next 10 to 20 years
Manufacturing processes	<ul style="list-style-type: none"> • Investigate use of metals and other materials to manufacture grid components such as motors and transformers • Adapt soft magnetic materials for advanced manufacturing • Develop structural composites that are lightweight, high-strength, and failure-proof, to reduce weight and installation costs and enhance reliability 	<ul style="list-style-type: none"> • Near term (1-5 years) because these advanced materials and manufacturing methods may help to address the end of expected useful life of existing infrastructure

R&D Technology Area	Recommended R&D	R&D timeline
Transformers	<ul style="list-style-type: none"> • Develop methods for cost-effective large-scale manufacturing of conductors and connectors • Develop cost-effective large-scale manufacturing of conductors and connectors using metallic matrix composite materials with improved electrical and mechanical properties • Develop processes for manufacturing carbon nanotubes and carbon nanotube-based conductors using low-cost abundant precursors, such as coal and natural gas, for manufacturing connectors to electrical systems for a novel class of cables. 	
	<ul style="list-style-type: none"> • Modular transformers: <ul style="list-style-type: none"> ◦ Standardize modular transformers is needed so that they can be transported to any substation or utility without the need for redesign ◦ Develop customizable components (possibly through specific power electronics) allow the transformer's performance characteristics to meet specific needs 	<ul style="list-style-type: none"> • Near term (1-5 years) to enable rapid deployment of transformers in response to an event

*EIA = Energy Information Administration; SiC = silicon carbide; BaTiO₃ = barium titanate; ZnO = zinc oxide; HVDC = high-voltage direct current

Advanced Sensors

The electricity grid relies heavily on monitoring, such as supervisory control and data acquisition (SCADA) and wide-area monitoring systems that track grid status as well as sensors that monitor grid equipment. Advanced grid sensors play a significant role in the reliability, resiliency, and security of the grid. DOE has been playing a vital role in advancing grid measurement technologies. For example, Smart Grid Investments under the American Recovery and Reinvestment Act of 2009 have supported the installation of more than 1,000 phasor measurement units across North America. Through a partnership between industry and DOE, the North American SynchroPhasor Initiative has been improving power system reliability and visibility through wide-area measurement and control. These efforts have greatly improved situational awareness and visibility of the transmission system during the past two decades. However, widespread deployment of advanced sensors and their integration within power system control rooms remains slow. R&D efforts are needed to improve measurement availability and reliability in addition to reducing installation and integration costs. Policy and regulatory action can help accelerate the adoption of mature sensor technologies. We highlight three research topics that are critical to monitoring to ensure a safe, reliable electricity grid: high-fidelity sensors, asset monitoring, and advanced timing.

Key R&D areas for advanced sensors include:

- High-fidelity sensors, including intelligent and multi-functional synchronized measurement devices and optical voltage and current transducers
- Grid asset monitors with embedded sensing, advanced manufacturing and seamless system integration, wireless sensing, and communications
- Advanced timing technology with high security, reliability, and accuracy

Table ES-5 describes the R&D recommended for each of the above three areas.

Table ES - 5. Advanced Sensors R&D Recommendations

R&D Technology Area	Recommended R&D	R&D timeline
High-fidelity sensors	<ul style="list-style-type: none"> • Synchronized measurements <ul style="list-style-type: none"> ○ Develop timing technologies that do not rely on the global positioning system or alternative timing technologies for synchronized measurements ○ Develop application-driven synchronized measurement technologies to enable overall monitoring system performance to meet the needs of power system applications ○ Develop measurement intelligence, including measurement algorithms intelligence and distributed measurement intelligence, enhancing measurement accuracy, reliability, availability, security, and versatility ○ Develop multiple measurement functions in one device, including synchronized measurements, point-on-wave measurements, power quality measurements, transients, and dynamics recording ○ Develop extremely low-computational-cost measurement methods to enable ubiquitous synchronized measurements of various grid equipment • Optical monitoring systems <ul style="list-style-type: none"> ○ Develop an optical sensor characterization platform to comprehensively evaluate the performance of optical devices under various grid operation conditions; compare optical sensor performance with traditional potential and current transformers to justify optical devices' advantages ○ Perform long-term field testing of optical devices to justify their performance, e.g., by installing optical sensors at substations and integrating them with devices such as relays, power quality analyzers and phasor measurement units, with utilities' participation and feedback ○ Address the data interface between optical sensor devices and legacy grid devices. ○ Reduce the cost of optical devices to enable them to compete with traditional devices. ○ Conduct pilot projects to demonstrate the advantages of optical devices over traditional devices, e.g., using a multiple-parameter grid monitoring system incorporating optical devices to address high-impact real-world problems that industry and utilities face, such as wildfire detection and mitigation and large power transformer partial discharge detection and location 	<ul style="list-style-type: none"> • Synchronized Measurements: Near term (1-5 years) to overcome the challenges that prevent applications of synchronized measurements in control rooms for real-time grid control and protection • Optical monitoring systems: Near term (1-5 years). because optical monitoring systems have many advantages that potential and current transformers lack and their adoption could improve grid measurement resolution, safety, and reliability, and enable monitoring of multiple parameters
Asset monitoring	<ul style="list-style-type: none"> • Develop embedded sensing for asset monitoring, including co-design and seamless integration of sensing method and asset structure into manufacturing • In developing sensors, consider system-level design and interfaces for autonomous initiation, data processing, self-calibration, and energy management for self-sustained operation; successful technology transfer to manufacturing and market acceptance will depend on the synergy between the system functionality and manufacturing techniques • Develop next-generation multi-functional sensor platforms 	<ul style="list-style-type: none"> • Near term (1-5 years) because embedded sensing and seamless system integration of asset monitoring with advanced manufacturing could help improve penetration of asset monitoring in energy systems

R&D Technology Area	Recommended R&D	R&D timeline
	<ul style="list-style-type: none"> • Develop wireless protocols that align with goals of smart grid technology • Develop dynamic line rating (DLR) technology with prediction capability for a wide range of time frames; ensure that DLR products are easy to integrate into the existing transmission system; identify high-value DLR application(s) in control rooms; collaborate closely with utilities and industry • Develop or adopt methods to assess or manage the potential risks associated with new tools and methods or propose methods to be used for qualification of new technologies. • Investigate AI as a promising technology to enable DLR with a high-accuracy forecasting capability from the hourly to the daily time frame. 	
Advanced timing	<ul style="list-style-type: none"> • Develop pulsar-based timing instrument and pulsar-based timing applications for the grid • Develop hybrid timing system(s) that can be coordinated when the global positioning system (GPS) timing signal is unsatisfactory, to give more precise, reliable synchronization • Develop time shift detection and alignment • Develop timing system spoof detection and protection; mitigate the spoofing vulnerability in GPS and other timing sources. 	Near term (1-5 years). Timing is a fundamental component for data synchronization for grid monitoring.

R&D = research and development; DLR = dynamic line rating; GPS = global positioning system

Advanced Protection Systems

As power delivery systems evolve, so must the devices, methods, and schemes that protect those systems. Fundamental characteristics that have defined the grid and associated protection schemes for the past century no longer hold true in many cases, and operational expectations are increasing in both distribution and transmission. Distributed energy resources, such as solar photovoltaics and wind generation, are being introduced to the system at an ever-increasing rate. At the same time, technological advances such as modern communication architecture, advanced sensors, and a trend toward system-wide interoperability provide many opportunities to modernize protection schemes to handle today's added complexity.

The relay protection system of the future will need to be:

- Flexible enough to handle complex topologies and operational requirements
- Able to incorporate communication while being robust against cyber-physical threats
- Less dependent on overcurrent protection than today's systems
- Sensitive enough to detect faults and reliable enough to avoid mis-operations

DOE and Oak Ridge National Laboratory produced a document in 2019, with input from more than 70 participants from industry, academia, and national laboratories, entitled "Roadmap of Protective Relaying for the Future." That document presents a plan for ensuring that transmission and distribution

system protection schemes will be designed, installed, operated, and maintained to accommodate all new technologies impacting the electric grid in the near and distant future. Much of the summary of R&D recommendations in Table ES-5 is based on that plan.

Table ES - 6. Advanced Protection Systems R&D Recommendations

R&D Technology Area	Recommended R&D	R&D timeline
Model-driven adaptive relaying	<ul style="list-style-type: none"> Develop approach to incorporate an internal power system simulator within local relays, which can automatically calculate protection settings and adjust coordination with both local and remote terminals; protective relays should be able to adaptively coordinate for multiple contingencies and configurations of the power system they are protecting 	<ul style="list-style-type: none"> Near term (1-5 years(to allow time for development, commercialization, and adoption
Artificial intelligence/machine learning	<ul style="list-style-type: none"> Develop algorithm for auto-tuning models or learning expected load level, to characterize and provide accurate parameters by learning normal system behavior as well as system response during system breaker operations, fault events, and normal operations Incorporate mitigations techniques for system configuration when position navigation and timing series are not available, to support resilience and mitigation during these times 	<ul style="list-style-type: none"> Near term (1-5 years) to allow time for development, commercialization, and adoption
Setting-less (coordination-less) relay	<ul style="list-style-type: none"> Develop protection based on dynamic state estimation (sometimes called “setting-less protection”), in order to avoid complex settings and coordination tasks, reduce errors, and continuously monitor protection zone measurements; a mismatch between measured data and the dynamic model would indicate that something is wrong inside the protection zone 	<ul style="list-style-type: none"> Mid term (10-15 years)
Integration with sensors (traditional and non-traditional)	<ul style="list-style-type: none"> Develop sensors that measure physical quantities other than voltage and current, e.g., acoustic, vibration, and thermal sensors 	<ul style="list-style-type: none"> Mid term (10-15 years)

To accommodate ongoing and impending changes to the grid, R&D work needs to begin as soon as possible.

Role of the United States Department of Energy

DOE, specifically the Office of Electricity, plays an instrumental role in bridging the innovation gap (a.k.a. the “valley of death”) by means of public -private partnerships among industry, utilities, and research organizations such as national laboratories. DOE can address immediate and long-term challenges to America's energy security while supporting applied research on advanced technologies. Additionally, DOE can use its convening power to bring together stakeholders and further refine the areas addressed in this report, federal investments that can have the most significant impact.

As this white paper outlines, several key transmission technologies are needed to meet the requirements of the future transmission grid. DOE support will be instrumental in realizing these advances. Table ES-7 summarizes DOE’s roles for each of the four R&D areas we have identified.

Table ES - 7. Role of DOE in Advancing Transmission Technologies necessary to meet the Requirements of the Future Transmission Grid

R&D Technology Area	Recommended Role of DOE
Power System Electronics	
FACTS-based power-flow control devices	<ul style="list-style-type: none"> • Assist R&D for continuously improving the reliability and cost performance of FACTS technologies • Facilitate industry coordination and collaboration to promote field demonstrations of advanced FACTS devices • Assist in the transition to full-scale demonstrations and comprehensive field applications of hybrid low-cost devices • Coordinate development of testbeds or testing facilities • Support development of comprehensive simulation tools/frameworks to facilitate modeling and analysis of the technologies
Embedded HVDC systems	<ul style="list-style-type: none"> • Encourage and assist industry to expand field demonstrations of embedded HVDC systems • Facilitate collaborations between industry and academia on researching multi-terminal DC (MTDC) applications such as continent-level interconnection, renewable energy integration, and urban power grid uprating • Develop testbeds and testing facilities for validating new technologies used in HVDC applications and identifying viable technology routes • Hold workshops for utilities, regulatory bodies, and government to introduce latest MTDC technology progress
Power electronic building blocks for multiple applications	<ul style="list-style-type: none"> • Support development of power stage subsystem common architectures that can be used across multiple applications, as well as designs that integrate multiple functions into one
High-Power Delivery Over Long Distances	
Electrical conductors	<ul style="list-style-type: none"> • Support near-term public-private partnerships to accelerate deployment of advanced conductor technologies • Support demonstration of advanced technologies to increase ampacity along existing corridors
Electrical insulators	<ul style="list-style-type: none"> • Support near-term public-private partnerships and encourage adoption of technology through demonstration activities
Manufacturing processes	<ul style="list-style-type: none"> • Bring together industry, academia, and national laboratories to identify novel approaches using innovative manufacturing processes, such as advanced manufacturing. • Establish an advanced materials program focused on development of new materials and processes such as: <ul style="list-style-type: none"> ○ Soft magnetic materials adapted for advanced manufacturing ○ Structural composites that are lightweight, high strength, and failure-proof, to reduce weight and installation costs while enhancing reliability ○ Cost-effective large-scale manufacturing of conductors and connectors using metallic matrix composite materials with improved electrical and mechanical properties ○ Processes for manufacturing carbon nanotubes and carbon nanotube-based conductors using low-cost abundant precursors, such as coal and natural gas, and processes for manufacturing connectors for integrating these novel classes of carbon nanotubes and carbon nanotube-based cables into electrical systems.
Transformers	<ul style="list-style-type: none"> • Support public-private partnerships to advance and accelerate testing and deployment of transformers, including modular transformers • Promote collaboration with DOE's Advanced Manufacturing Office with equipment manufacturers and utilities towards the development of modular transformers • Support development on new insulation materials, low-loss magnetic core materials, electrical conductors for windings, and cooling of transformers
Advanced Sensors	
Synchronized measurements	<ul style="list-style-type: none"> • Support deployment of timing technologies, including long-term performance demonstration, system-level integration of multiple time sources, and benefit-cost analysis

R&D Technology Area	Recommended Role of DOE
	<ul style="list-style-type: none"> Promote collaborative efforts among research organizations, industry, and utilities to define and quantify requirements for synchronized measurements, to guide development of synchronized measurement technologies. Develop a strategy that makes it easy to share data among different organizations, for developing measurement intelligence and other artificial intelligence applications for power systems
Optical monitoring systems	<ul style="list-style-type: none"> Accelerate application of optical potential transformers/current transformers in power systems by facilitating close collaboration among national laboratories, industry, and DOE
Asset monitoring systems	<ul style="list-style-type: none"> Work closely with utilities to identify high-value applications of DLR in system operations; promote industry partnership to commercialize DLR in the United States.
Advanced timing	<ul style="list-style-type: none"> Promote collaboration among R&D organizations, industry, and utilities to determine the market potential and barriers to new timing technologies
Advanced Protection Systems	
	<ul style="list-style-type: none"> Promote and coordinate government, research organization, industry, and utility collaboration on defining needs and requirements for advanced protection systems Promote and coordinate, across DOE, co-simulation and model integration to ensure that model results account for system dynamics Coordinate industry collaboration to ensure that newly developed equipment is backward compatible; collaborate with research organizations, DOE, and industry to define equipment compatibility requirements

R&D = research and development; DOE = U.S. Department of Energy; FACTS = flexible alternating current transmission system; HVDC = high-voltage direct current; DLR = dynamic line rating; MTDC = multi-terminal direct current

1. Introduction

1.1 Purpose and Scope

The U.S. electricity grid is arguably one of the most complex machines ever made [4], and according to the National Academy of Engineering, “the greatest engineering achievement of the 20th century” [5]. From a historical perspective, the electric power system in the United States evolved during the first half of the 20th century without a clear awareness of the system-wide implications of its evolution [6]. Since 1940, the energy consumed to generate electricity has risen from 10% to 40% of the total energy consumed, as electric power systems have become a fundamental component of our modern infrastructure [6]. As society becomes more electrified, the fraction of energy dedicated to electricity generation is expected to increase further. Looking forward, the energy delivery system faces many challenges from an evolving generation mix, aging infrastructure, integration of new technologies with legacy systems, and increased threats to its infrastructure.

This white paper focuses on transmission technology hardware and components to help ensure the reliability and resiliency of the grid of the future. To determine priority transmission technologies for R&D focus, we developed future grid scenarios and identified technology solutions that would be essential in each scenario. The technologies identified as solutions in multiple scenarios are power-flow control systems (reactive power devices, power electronic components), high-power delivery technologies (e.g., advanced conductors, high-voltage, direct-current [HVDC] systems, transformers), advanced sensors, and advanced protection systems. This paper describes the current status of these technologies, their role on the future grid, and recommendations for U.S. Department of Energy (DOE) investment in research and development (R&D) to support them.

Some technology areas that will be essential for the future grid are omitted from this white paper because they are being addressed elsewhere: an energy storage R&D roadmap is being addressed within the Energy Storage Grand Challenge; cyber security R&D roadmap activities fall under the Office of Cybersecurity, Energy Security, and Emergency Response; energy management systems, advanced controls, and technology related to policies and markets are addressed in other white papers in the series to which this paper belongs.

1.2 Scenario Analysis to Identify Key Transmission Technologies

To identify priority transmission technologies for federal investment and public-private partnerships, our team analyzed multiple potential pathways that the future grid could take. We summed those pathways into four scenarios and identified technology solutions that could address the challenges outlined in each scenario. The technology solutions that rose to the top in the largest number of scenarios are evaluated in this white paper.

The four future scenarios, which were defined to capture major trends that would have significant implications for future grid infrastructure and operations, are:

- A more distributed grid

- Increased clean energy with high penetration of variable renewable energy
- Increased load growth with re-establishment of U.S. manufacturing base
- Cyber and physical vulnerabilities and threats to the grid

Table 1 summarizes the scenarios with a description of the nature of each, the challenges addressed within each, and potential solutions identified to address those challenges.

Table 1. Summary of Scenarios

Scenarios	Description	Challenges	Solutions
Distributed	Numerous drivers push toward a more distributed grid. As intermittent resources such as wind and solar become more common, traditional base-load plants such as coal and nuclear become less economically attractive. Utility customers transition from passive to active participation. Falling costs of both distributed energy resources and distributed storage motivate customers and utilities to consider these non-wire alternatives for resiliency, reliability, and congestion relief. Technological advances and more educated consumers create grid-interactive loads that can consume electricity intelligently.	<ul style="list-style-type: none"> • Planning challenges related to increase in distributed generation that is not governed by transmission/bulk generation regulations • Decreased revenue for transmission system owners/decreased need for new transmission lines (i.e., change in business model) • Responsibility to maintain system stability and reliability with reduced base load • Imbalance, volatility, and other transmission impacts from distributed generation • High relative need for, and flexibility of, reactive power compensation 	<ul style="list-style-type: none"> • Improved transmission/distribution simulation • Advanced adaptive protection schemes • Networked microgrid control schemes • Distributed power-flow devices • Advanced dynamic reactive-power sources
Clean Energy	Utilities embrace decarbonization along with unprecedented policy changes that dramatically alter the generation mix and result in further adoption of renewable technologies, reduction and decommissioning of all coal-fired power plants, and a resurrection of nuclear power plants.	<ul style="list-style-type: none"> • Generation location and alignment with load centers • Changes in power flow across the country • Localized reactive power issues • Grid flexibility response (inertia, voltage, frequency, and load/generation response) 	<ul style="list-style-type: none"> • Power electronic technologies for power-flow control • Advanced conductor and underground systems • Long-distance energy transfer
Industry Boom	Manufacturers pursue energy efficiency and sustainability, but the overall electricity consumption increase would be substantial if the scale of the manufacturing recovery is large enough. Local load may spike rapidly at some manufacturing	<ul style="list-style-type: none"> • Ability to predict scale, type, and location of manufacturing growth and electricity consumption • Uncertainties about manufacturing growth, which affect transmission planning 	<ul style="list-style-type: none"> • Advanced load-estimation and prediction technologies (data/artificial intelligence-based) to support transmission planning and operation • Transmission line uprating technologies (e.g., high-temperature conductors,

Scenarios	Description	Challenges	Solutions
	centers as manufacturers come back online or expand, adding uncertainty to mid- to long-term transmission planning. Transmission capacities may be exhausted by load growth if planning assumptions are significantly different from what actually happens. Advances in logistics and communications may continue to relax geographical restrictions on manufacturing supply chains, which may not necessarily be aggregated in terms of location. Electrical loads at manufacturing centers may correlate closely with loads of distant supply chains. This will create challenges for load prediction, dispatch, and transmission planning.	<ul style="list-style-type: none"> • Intermittent load patterns of future mass manufacturing posing difficulties for load predictions and dispatch/operation • Potential that manufacturing growth will exhaust transmission capacity • Load behaviors correlate over wide geographic areas • Low-power-factor loads (inductive loads) posing challenges for reactive power compensation and related regulations 	<p>high-emissivity coatings) to increase transmission capacity in relatively short period of time</p> <ul style="list-style-type: none"> • Advanced dynamic rating of transmission lines and transformers to improve use rate of existing lines • Advanced reactive-power compensations to accommodate low-power-factor loads • Flexible alternating current transmission systems and other advanced power-flow control • Microgrid and energy storage to reduce the burden of power transfer
Cyber and Physical Vulnerabilities and Threats	As the national interconnected electric grid becomes increasingly dependent on computers and data sharing, resulting in significant benefits for utilities, customers, and communities, the grid will also become more vulnerable to both physical and cyber threats. Defenses for all types of critical infrastructure control systems, including water, gas, and transportation, must improve just to keep pace. The North American Electric Reliability Corporation defines a bulk electric system cyber asset as one that, if rendered unavailable, degraded, or misused would (within 15 min. of its required operation) cause mis-operation, non-operation, or adversely impact one or more facilities, systems, or pieces of equipment, which, if destroyed, degraded, or otherwise rendered unavailable when needed, would affect the reliable operation of the bulk electric system [1] [2].	<ul style="list-style-type: none"> • Cost of hardening infrastructure to prevent attacks • Developing ways for utilities to cost-effectively address risks without “gold-plating” the system 	<ul style="list-style-type: none"> • Install sensors to increase visibility on both operational technology and information technology systems, with cyber security built into sensor designs • Use unmanned aerial vehicles to assist with restoration after extreme events • Use technologies including mobile transformers to improve restoration services • Harden infrastructure using novel materials for grid components (e.g., through advanced manufacturing) • “Retrofit” critical grid equipment with analog and manual technologies as a defensive measure against cyber attacks

Our recommendations for future R&D investment are centered around several key technologies that consistently emerged from our analysis as addressing the conditions of these extreme scenarios:

- **Power-flow control devices:** Transmission-scale reactive power devices, low-cost hybrid systems and energy storage, power electronic building blocks for multiple applications such as flexible alternating current transmission system (FACTS) devices, solid-state transformers
- **High-power delivery systems to transmit over long distances:** Ultra-conductive systems, smart materials such as material systems fabricated using advanced manufacturing (AM) technologies, transformers, wireless power transfer, superconductivity
- **Advanced sensors:** High-fidelity sensors, asset monitoring (non-destructive evaluation, drone survey of lines), alternative timing
- **Advanced protection systems:** Model-driven adaptive protection systems, negative sequence source and alignment to advanced sensor and communication technologies

1.3 Previous Work on Identifying Technologies for R&D

A number of changes under way are increasing the grid's capacity to provide necessary services but also potentially create instability. These include: changes in generating mix; growth in distributed energy resources (DER) on the grid; and proliferation of electric vehicles, smart buildings, and other similar distributed loads that can also function as energy sources. These changes will require continual re-evaluation of future bulk power system needs. DOE and other organizations have previously evaluated the state of the grid and identified research, development, and demonstration (RD&D) focus areas. Previous evaluations include the following documents:

- Grid 2030 – A National Vision for Electricity's Second Hundred Years (DOE Office of Electricity 2003)
- National Electric Delivery Technology Roadmap (DOE Office of Electricity 2004)
- Grid of the Future Challenges and Opportunities (MIT 2011)
- Quadrennial Technology Review (DOE 2015)
- The Future of Electric Power in the United States (National Academies 2021)

APPENDIX A presents a full summary of each the 2003/2004 (related reports), 2011, 2015, and NAS reports listed above.

Table 2 summarizes technology recommendations from the 2004, 2011, and 2015 reports listed above. Many of the technology areas and recommendations have not changed dramatically since the reports were published. Although there have been advances, challenges remain in improving the reliability and performance of these technologies while reducing their cost to facilitate market adoption. As described throughout this white paper, there is close alignment among the R&D recommended in previous reports and the recommendations in this report in the areas of power electronics, conductors,

protection systems, and sensors. (The most recent National Academies report also highlights power electronics (inverters, direct-current transmission) and advanced grid protection as key technologies [3].)

Table 2. Summary of Previous R&D Recommendations

2004 Roadmap	2011 MIT Report	2015 QTR
Advanced conductors	Energy management systems integrating phasor measurement units	Control systems
High-temperature superconductors	Advanced control schemes	Advanced transformers
Electricity storage	Flexible alternating current transmission systems	Power-flow controllers
Distributed intelligence and smart controls	Information and communication	Protection equipment
Power electronics		Advanced cables and conductors

1.4 Organization of the Paper

The remainder of this white paper is organized as follows:

- Section 2 describes in detail the selected technology areas and specific R&D recommendations for each.
- Section 3 summarizes our overall R&D recommendations and conclusions.
- Section 4 presents the references cited in the paper.
- Appendix A presents R&D recommendations from previous reports.
- Appendix B describes our scenario analysis method.
- Appendix C lists the future scenarios we considered.
- Appendix D describes promising designs for power grid circuit breakers.

2. Transmission Technologies

Based on our scenario analysis, we identified four broad, high-impact technology goals for modernizing the grid that are not addressed in other DOE programs: 1) Developing and incorporating power electronics and associated building blocks; 2) Improving ampacity across the system (through advanced conductors, next-generation components such as transformers, and hardening the infrastructure utilizing novel advanced materials and manufacturing technologies); 3) Increasing observability using a balanced mix of high-fidelity sensors and low-cost monitoring devices; and 4) Developing overall protection and relay systems using smart technologies/inverters.

For the four broad technology goals listed above, we identify four key types of technologies that we believe merit DOE support. Those technologies and the related recommendations for DOE support are summarized below and then described in detail in the subsections that make up the remainder of this section of the paper.

1. **Power-Flow Control Devices:** Power-flow control will be essential for the future grid, helping to maintain basic operations, improve infrastructure utilization, ensure power quality, relieve power congestion, increase stability, and avoid power outages. Although power-flow control devices are currently in a state of relatively lower readiness compared to some other technologies for the future grid, and in that sense, they could be considered the subject of longer-term research activities, we recommended that DOE initiate R&D efforts in the following areas in the near term:
 - FACTS-based devices
 - Embedded HVDC
 - Power electronic building blocks
2. **High-Power Delivery for Improved Resilience and Reliability:** To address renewable integration and a changing generation mix, we recommend that public-private partnerships be formed to increase ampacity along existing corridors. A large proportion of transmission lines in the United States were constructed more than 60 years ago, are based on 1950s' technology, and are not engineered to meet today's grid requirements. Technologies recommended for R&D include:
 - Conductors, ultra-conductors, and dielectric components
 - Advanced manufacturing
 - Transformers, including modular transformers
3. **Advanced Sensors and Sensor Systems:** Electricity system operations rely heavily on grid measurements, and grid visibility is vital to the reliability, resiliency, and security of the system. Near-term, public-private partnership investments can accelerate advancements in grid monitoring systems. We recommend that DOE support research in the following areas:

- High-fidelity sensors to be used along with low-cost monitoring devices
 - Asset monitoring
 - Advanced timing
4. **Advanced Protection Systems:** Fundamental characteristics that have defined the grid and associated protection schemes for the past century no longer hold true, and operational expectations are increasing. The relay protection system of the future will need to be flexible, sensitive enough to detect faults and avoid mis-operation, and equipped with advanced, robust communications. Areas of R&D recommended to advance grid protection systems are:
- Model-driven adaptive relaying
 - Artificial intelligence/Machine learning (AI/ML) applied to advanced protection
 - Setting-less (coordination-less) relays
 - Integration of traditional and non-traditional sensors

The following subsections address each of the above topics: Section 2.1 focuses on power-flow control devices, Section 2.2 on high-power delivery, Section 2.3 on advanced sensors, and Section 2.4 on advanced protection systems. For each types of technology, we present:

- An overview of the technology and its importance to the grid
- The current state of the technology and barriers to its evolution
- Specific topics for R&D with recommendations for DOE's role
- A summary of R&D recommendations

2.1 Power-Flow Control Devices

As noted above, power-flow control is critical to maintain basic grid operations, improve infrastructure utilization, ensure power quality, relieve power congestion, increase stability margins, and avoid power outages. Insufficient or no power-flow control can cause operation abnormalities, which can have significant economic costs. Power-quality issues (90% due to voltage drop) annually cost U.S. industry more than \$20 billion [7]. A power outage at a financial data center could cost \$10 million per minute [8]. Comprehensive power-flow control could have major operational and economic benefits, significantly boosting the transfer capacity of a transmission line, thus increasing the overall utilization rate of the transmission grid and deferring the need to build new lines. Studies show that only half of the more than 300,000 miles transmission lines in U.S. are utilized at any given time [9]. The median cost for adding new transmission capacity to accommodate renewable generation is about \$300/kW [10], exceeding the cost of the most expensive FACTS devices. Wide use of power-flow control not only expand grid capacity without adding new lines but would also make the grid more flexible and resilient to accommodate a variety of future scenarios.

Providing adequate, optimal power-flow control has been difficult for several reasons. One is that electrical energy is difficult to store in large quantities, and electricity must be generated at the same time that it is consumed. Load demands vary continuously, at time scales ranging from seconds to seasons, and some generation also varies continuously.

Power-flow control is realized by regulating the bus voltage (magnitude and/or phase angle), line impedance, active/reactive power, or any combinations of these items. The complexity and cost of a power-flow control device generally correlate positively with the number of parameters the device can regulate; the more the device can do, the more complex and expensive it is. Power-flow control devices must be selected based on site-specific requirements and performance and cost considerations. Existing power-flow control technologies can be categorized as voltage magnitude regulators, phase (voltage) shifters, reactive-power compensators, and comprehensive power-flow controllers. Many power-flow control devices use conventional electrical devices, such as power transformers and synchronous machines, as the main body to implement the control mechanism and take the full-rating power. Examples include synchronous condensers and tap-changing or phase-shifting transformers.

In this section, we highlight specific R&D areas relevant to power-flow control. Recommendations for government support cut across three areas: 1) FACTS-based devices, 2) embedded HVDC, and 3) power electronic building blocks. Historically, these areas have been funded through federal programs, such as DOE's Advanced Research Projects Agency–Energy, the Defense Advanced Research Projects Agency, and industry research efforts. However, these past efforts have been nominal compared to what is needed to achieve the performance and cost characteristics required for wide market adoption of this technology.

2.1.1 FACTS-based Power-Flow Control Devices

FACTS devices encompass a wide range of controllers that incorporate semiconductor-based power electronics systems for electric power applications [8] [9]. With different designs, FACTS devices can provide different levels of power-flow control capability. Since the FACTS concept was introduced in the mid-1980s, FACTS devices have evolved through three generations. Table 3 summarizes general information about both electric-machine-based and FACTS-based technologies [10] [11] [12] [13] [14]. Cost and reliability are the most critical factors affecting adoption of FACTS technologies, especially considering the low cost and excellent reliability of conventional iron-core-based technologies such as power transformers. First-generation FACTS devices were low cost and are widely deployed on the grid although their control functions are usually coarse. The later generations feature more advanced control functions but were much more expensive.

Table 3. Power-Flow Control Technologies Currently Used on the Grid

Technologies	Typical devices*	Functionalities	Control Type	Cost Range (\$/kVA)**
Electric-machine based	LTC, PST (or PAR), synchronous condenser	Voltage regulation, power-flow control, reactive-power compensation	Stepwise, continuous	10~20
1st gen. FACTS	SVC, TSC, TSR	Reactive-power compensation, voltage regulation, limited dynamic and transient capability	On/off or stepwise	15~60
2nd gen. FACTS	TCSC, STATCOM, SSSC	Real and reactive-power compensation, voltage/current regulation, oscillation damping, limited dynamic and transient capability	Continuous	50~150
3rd gen. FACTS	UPFC, IPFC	Full power-flow control, flow direction reversal, voltage/current control, oscillation damping, fault current limiting, full dynamic and transient capability	Continuous	100~200

* LTC = load tap changer; PST = phase-shifting transformer; PAR = phase angle regulator; SVC = static volt-amp reactive compensator; TSC = thyristor-switched capacitor; TSR = thyristor-switched reactor; TCSC = thyristor-controlled series capacitor; STATCOM = static synchronous compensator; SSSC = static synchronous series compensator; UPFC = unified power-flow controller; IPFC = interline power flow controller; kVA = kilovolts ampere

** Per throughput power

Electric-machine-based power-flow control devices have been in common use on the grid for a long time. In many cases, there are counterparts within the FACTS family that can substitute for electric-machine-based devices, such as static synchronous compensators (STATCOMs) or synchronous condensers. The latter has recently seen a resurgence of interest for addressing inertia issues caused by deepening penetration of converter-based sources on the grid [15] [16]. However, this type of application is more of a system control problem that is not likely to attract extensive R&D on the device hardware, which is the focus of this white paper.

The past decade has seen the emergence of a number of novel low-cost power-flow control technologies that are hybrids made up of conventional electric machines (to take the main throughput power) and low-rating FACTS devices (to implement the control). These hybrid devices exhibit the high efficiency and reliability of the electric machine while avoiding the use of expensive full-rating power electronics. This combination significantly reduces their cost compared to the cost of advanced FACTS devices; the lower cost makes large-scale deployment affordable. The cost of advanced FACTS is not expected to drop sufficiently to enable full-scale deployment of this technology during the next 20 years. This leaves opportunities for the low-cost hybrid technologies to be deployed until advanced FACTS devices become a feasible option for wide-scale deployment. The continuous variable series reactor, metal-oxide-semiconductor-controlled thyristor, and distributed FACTS [17], [18], [19], [20], [21], [22] are examples of low-cost devices that are currently at different technology readiness levels. A

transmission-level continuous variable series reactor prototype was developed in 2015 but has not yet been demonstrated in the field. Distributed FACTS are currently being applied in two utilities' networks.

In addition to hybrid devices, another type of low-cost power-flow control device is a fault current limiter (FCL). During a system fault, fault currents can reach more than 100 times the normal operating current. An FCL can rapidly insert a large resistance or reactance into the transmission line to absorb the excessive energy and limit the current. FCLs are usually designed to limit fault currents to three to five times the steady-state current. FCLs can be integrated with other power-flow control devices such as unified power-flow controllers (UPFCs) to reduce the fault burdens imposed on those devices and thus allow for them to have a lower design rating than would otherwise be required.

2.1.1.1 Challenges and R&D Targets

Device reliability and cost: Commercial applications of advanced FACTS devices have been few because of the devices' extremely high ownership cost and concerns about their reliability. The single point of failure of the power electronics module yields reliability lower than the typical 99.99% reliability expected of utility operations [23]. The newer FACTS devices have more components, more complex configurations, and therefore are possibly even less reliable than older models. In addition, advanced FACTS devices require much more maintenance than conventional technologies to ensure reliability, which further increases their total ownership cost. A trade-off is needed between desired performance and cost. Lowering the cost and improving the reliability of advanced FACTS devices will continue to be critical R&D topics in the coming decades.

Bi-directional power flow between transmission and distribution systems: Some researchers envision the future grid having an integrated, decentralized configuration, with local distribution networks operated by distribution system operators and connected to their peers as well as to the bulk transmission grid for energy trading and reliability services [24]. Most DER will be integrated into distribution systems and participate in distribution markets. End users will be able to both consume and generate power or to switch between the two modes seamlessly. All of these new features may result in bi-directional power flow between the transmission and distribution systems, in contrast to the traditional configuration in which there is one-way flow with the distribution system effectively acting as a load on the transmission system. Devices controlling power flow between the systems will have to account for this change.

Integrated modeling and design: Operation of FACTS devices involves intricate electromagnetic processes across a frequency range from direct current (DC) to pulse frequencies and accompanied by other physical processes such as heat transfer. The temporal granularities and electromagnetic characteristics of these subsystems or processes vary substantially, making it challenging to represent them in modeling tools. Many related commercial tools focus on specific areas and cannot model the complexities of the physics of FACTS devices. There is no comprehensive tool, or framework for integrating existing tools, that can model FACTS devices accurately. Licensing issues can also complicate integration of tools. DOE has successfully in coordinated and supported development of similar tools/frameworks in other areas (e.g., GridLAB-D and the Microgrid Design Toolkit). We believe DOE

should play a similar role to help address the problem of modeling FACTS devices. This modeling discussion applies similarly to embedded HVDC systems (see Section 2.1.2).

2.1.1.2 R&D Recommendations for FACTS-Based Power-Flow Control Devices

Accelerating the maturation of advanced FACTS devices

To accelerate the pace at which advanced FACTS devices mature, DOE could promote field demonstration projects. Sufficient field demonstrations will help accelerate technology acceptance, lower average cost, and boost stakeholder confidence. Maturity of the advanced FACTS especially rely on the R&D iterations through the field demonstrations. For example, after three early pilot projects in 1990s ~ 2000s (two in the United States., one in South Korea), there was very limited commercial applications of UPFC. The development of the technology had been in a slow-paced mode until recently when a number of commercial applications have been in operation or under construction/planning. (However, none of those is reported to be in the U.S [25] [26] [27].)

R&D on the building blocks of FACTS can also help the technologies mature. For example, modular multilevel converters (MMCs) based on advanced power electronics modules are likely to be the most popular topology of voltage source converters (VSCs), which can be used in multiple FACTS devices [28] and HVDC systems. Emphasis can be placed on R&D related to MMC-based VSC to benefit multiple applications.

Many power-flow control devices, especially low-cost models and advanced FACTS devices, suffer from lack of field testing because it is often impractical to test these devices on the actual power grid. Therefore, it is critical to develop testbeds that can facilitate the comprehensive testing of a variety of power-flow control technologies in an environment that realistically simulates field installations. Such testbeds will support rapid evolution of the technology. Supporting the development of testbeds aligns with DOE's mission.

Iron-core-based fault current limiters

Iron core-based FCLs, which operate automatically under fault conditions, are promising for many applications. They have relatively simple configurations and proven performance as well as excellent reliability and cost efficiency. Recent research has documented their potential for the DC grid [29]. Their core structures, coil optimization, and new strategies for implementing and controlling non-linear magnetization may need further R&D. Research would be beneficial on integrating FCLs with power electronics and permanent magnets to determine whether this combination can enable advanced control functions or improved magnetic characteristics.

Integrated use of fault current limiters with other power-flow control devices

By significantly reducing the magnitude of fault currents, FCLs can allow for lower fault ratings of other power-flow control devices and therefore allow for more choice. For example, FCLs can reduce the required ratings of DC circuit breakers when used together, allowing more choices of breaker types (e.g., solid-state) in HVDC applications. Protection coordination, optimal placement, and renewable integration impacts would all be valuable R&D areas.

2.1.2 Embedded High-Voltage Direct-Current Systems

2.1.2.1 Current Status, Challenges, and Barriers

An embedded HVDC system is defined as “a direct current link with at least two ends being physically connected within a single synchronous alternating current] AC network” [24]. Besides the typical functions that an HVDC system can perform, an embedded HVDC system can provide control functions such as power-flow control, voltage regulation, and system stability improvement [30] [31]. The converters in the HVDC system naturally provide fast, flexible power-flow control to the connected AC grid. Thus, an HVDC system can improve power-flow controllability and system stability (e.g., by damping system oscillation) as well as electricity market performance and generation utilization [32] [33]. Technically, an embedded HVDC system makes an excellent power-flow control solution. It can be economically viable and beneficial in certain applications although the capital investment to install it may be much higher than the cost of other power-flow control solutions.

The embedded HVDC system can be point to point, in parallel with an AC line to connect two nodes, or it can be a multi-terminal system implemented in the meshed AC grid. VSC-based systems are considered the most promising solution for multi-terminal HVDC (MTDC). VSC-based MTDC systems are have great potential for integrating renewable energy sources (e.g., offshore wind power) as well as providing advanced power-flow control functions. A combined VSC and line-commutated converter (LCC) system is also a potential solution that is attractive from the point of view of cost and technology maturity. For VSC topology, MMCs appear to be the most popular choice because of inherent advantages such as modularity, scalability, lower voltage ratings, high efficiency, and fault tolerance and blocking capabilities [34].

At the continental interconnection level, large-scale HVDC grids, such as the HVDC macrogrids proposed in the Macro Grid Initiative,¹ can provide significant operational and economic benefits, for example, interregional capacity exchange for improved resource allocation, infrastructure utilization, and energy arbitrage. Large-scale HVDC can also boost the reliability, ancillary services, and resilience of the regional power grid in extreme weather events such as the winter storm that caused the 2021 Texas power crisis. In regard to R&D, the control strategies and corresponding market framework of MTDC applications regulating services on multiple systems have not received much attention to date; research on these topics would benefit from DOE support.

A small number of commercial MTDC applications have been developed in recent years. More and more such applications are likely to be seen on the future grid. Those commercial applications are still to some extent used for testing and demonstration purposes. Sustained R&D in this area is a necessity.

2.1.2.2 Challenges and Research and Development Targets for Embedded High-Voltage Direct-Current Systems

For R&D related to embedded HVDC systems, especially the MTDC application, there are system and device-level challenges and barriers. Examples include operational feasibility of VSC/LCC hybrid converter stations; DC fault protection strategies (FCL, DC breaker, fault handling of overhead line and

¹ [Macro Grid Initiative - ACORE](https://acore.org/macro-grid-initiative/): <https://acore.org/macro-grid-initiative/>

mixed overhead/cable line, etc.); DC/DC converters for HVDC systems with different voltages; national transmission planning authority; and macro grid dispatch and control, resiliency, and security. Some of these challenges are discussed in more detail below.

DC fault current interruption: DC fault currents are more challenging to interrupt than AC fault currents because of the lack of natural zero-crossing points and the high rate of rise in the DC current. Most HVDC applications to date have used point-to-point configurations. The fault on the DC line can be interrupted either by the AC circuit breakers on the AC side of the system or by conventional DC interruption technologies, such as a high-speed neutral bus switch, high-speed round switch, metallic return transfer breaker, or ground return transfer switch. These DC interruption devices were all designed for, and used in, LCC-HVDC systems. None can interrupt the full fault current at a high voltage; hence, none are suitable for MTDC systems, in which DC fault interruption on the DC side is a necessity. The high-voltage DC circuit breaker is a fundamental building block of MTDC systems. R&D on this building block has become increasingly important as the MTDC technology develops.

Coordination with AC grid protections: Conventional AC grid protection systems are not designed for DC systems. We do not know enough about how to coordinate the protections for the AC grid and the HVDC system. MMCs have some level of inherent fault tolerance and blocking capabilities, but they are still susceptible to certain types of faults such as DC-side short circuit faults. There are challenges involved in identifying efficient protection schemes for embedded HVDC and the appropriate framework to coordinate with AC grid protections.

Lack of validation and field experience: Although HVDC is considered a mature technology, a VSC HVDC system may consist of many emerging technologies that have not been validated in the field. Currently, about 70 VSC HVDC applications are planned, under construction, or in operation worldwide [35] [36]. This limited number of field applications is not sufficient to validate these technologies [37]. MMC VSC-based HVDC was first put into operation in 2010, so we have only about 10 years of experience with this type of system. Testbeds that closely resemble actual field conditions or more field demonstrations and commercial applications are needed, to create a meaningful track record for these technologies. Although some studies, such as the Interconnection Seam Study² have shown the economic benefits of a continent-wide MTDC system, barriers to MTDC deployment in the United States are investment cost (or perceptions of cost) and the need for collaboration among states. The investment cost for HVDC technology has dropped significantly from its initial high, and the additional economic benefits brought by the technology balance some of the extra cost. HVDC technology shows profit advantages over HVAC in long transmission distance applications based on the findings of some studies, according to which the break-even point is estimated to be somewhere below 100km for various scenarios [38], [39]. However, MTDC systems are still often perceived as much more expensive than AC technology, which has, in part, contributed to limiting the field applications of MTDC systems.

² <https://www.nrel.gov/analysis/seams.html>

2.1.2.3 Research and Development Recommendations for Embedded High-Voltage Direct-Current Systems

Promoting field demonstrations

DOE could play an important role in coordinating field demonstrations, which, as noted above, will be key to enable rapid development of embedded HVDC technology. Given the R&D status of HVDC technology and the complexity of embedded systems, it might be infeasible for industry alone to develop the technology to the next level and transition it to widely available commercial applications.

Upgrading the AC grid /enhancing the grid with AC-to-DC conversion

Introduced around 2010, the concept of the AC-to-DC conversion allows AC transmission lines to be converted to HVDC lines to expand their power transfer capacity while maintaining existing tower structures, conductors, right-of-way, and grid topologies [40] [41]. The resulting HVDC system could provide all the benefits that an embedded HVDC system would provide. The Ultranet HVDC conversion project³ in Germany will, when commissioned, reportedly increase transfer capacity by up to four times. There are additional benefits of an HVDC system based on AC-to-DC conversion when used in the urban power grid; these benefits include reducing short-circuit currents, mitigating loop power flows, and enhancing control flexibility and system resiliency [28]. Studies have demonstrated AC-to-DC conversion's technical and economic benefits, indicating that the concept might be more widely relevant than currently thought. However, this technology has not drawn the attention of policy makers [42]. An important role for DOE would be to assist in R&D on topics such as operational impact analysis and integration of HVDC conversion in transmission planning tools, to facilitate field applications of this technology.

Advancing direct-current circuit breakers

DC circuit breakers are the main switching technology used to interrupt fault currents. The general strategy of a DC circuit breaker is to create zero-crossings in the fault current to facilitate the opening of breakers/switches. Zero crossings can be created by inductor-capacitor (LC) resonance or current commutation (into an alternative branch).

The most studied categories of high-voltage DC circuit breakers are mechanical and hybrid. A mechanical DC breaker typically consists of the mechanically operated circuit breaker and an LC branch in parallel to create a zero-crossing by means of LC resonance. Purely passive LC resonance may take time to build up and thus will slow the overall breaking process. It can be improved by pre-charging the capacitor or using a power-electronics-based active resonance circuit. A hybrid breaker usually consists of three branches whose functions are: (1) load conduction, accomplished by an ultra-fast switch for main isolation and a load-commutation switch for initiating fault current commutation; (2) fault current breaking, accomplished by the main breaker that is formed by a number of semiconductor switches; and (3) energy dissipation, accomplished by surge arrestors that dissipate the fault current energy. During a fault interruption, the fault current is commutated from the load conduction branch to the main breaker and then the energy dissipation branch until the fault current is extinct [43] [44] [45].

³ <https://www.amprion.net/Grid-expansion/Our-Projects/Ultranet/>

Operation time and normal conduction loss are the two key factors for assessing the performance of an HVDC circuit breaker. Faster breaker operation and less conduction loss are always preferred. In general, operation time within a 2- to 10-millisecond range is considered sufficient for future HVDC applications. Some popular/promising breaker designs are summarized in Appendix D. The research on identifying optimal breaker designs has explored and analyzed various breaker configurations, but field implementations have been very limited so far.

Some breaker designs, such as a mechanical breaker with current injection and at least three hybrid variants (classic, thyristor bidirectional, and insulated-gate bipolar transistor bidirectional), have been used in commercial applications. Mechanical circuit breakers with current injection are considered a mature, cost-efficient technology. Pure solid-state breakers feature fast operation time but have limited interruption capabilities and are costly. Due to these reasons, their applications are only feasible for the medium-voltage network for now. In the future, their applications in HVDC can become viable if there are breakthroughs in the current and voltage capabilities of semiconductor technologies'. Hybrid concepts will be the most promising in the near future because of their balanced performance in operation speed, conduction loss, and interruption capability.

DOE could make significant contributions to the evolution of DC circuit breakers by supporting demonstration projects and standards development. Another effort worthy of DOE support is research on the auxiliary components of DC breakers, such as an ultra-fast actuator for the mechanical breaker, a current-limiting inductor, and an auxiliary FCL. Improvements in these components would improve overall performance of the circuit breaker system and alleviate the current interruption rating requirements of the DC circuit breaker, i.e., expand its applications toward higher rating scenarios.

2.1.3 Power Electronic Building Blocks for Multiple Applications

In recent years, the cost of renewable energy and energy storage technologies has dropped exponentially as the technologies continue to mature and achieve market acceptance. This combination of factors has resulted in increasing deployment of DER and a shift from centralized generation systems toward distributed sources. This shift poses a key future challenge for the power grid as large generators that previously provided system energy needs and stability are replaced with large volumes of smaller, hierarchical systems (even large renewable plants consist of couplings of hundreds of power electronic systems into a single plant). In the past, DER represented only a small percentage of overall system capacity and could be incorporated into the grid without significant oversight. However, as the numbers of DER grow, increased coordination will be needed, and steps must be taken to ensure the reliability and efficiency of DER. Today's integration of renewables to support power transmission lacks the controllability necessary to support sustained reliability. Further advancements in HVDC and medium-voltage DC applications are needed to provide this controllability.

At the same time that penetration of DER and renewables is increasing on the grid, so is penetration of power electronics. This includes high-power drives (such as in Type-3 or 4 wind turbines and industrial drives) as the electronics in HVDC systems, FACTS devices, energy storage systems, inverter-based renewables like solar and wind, and electric vehicle chargers. Ongoing R&D in new power electronic technologies will further increase DER penetration. New technologies that are candidates for research

include, but are not limited to, solid-state power substations, extreme fast charging, solid-state transformers, and multi-port power electronics that integrate multiple sources/loads.

Power electronic systems can offer significant flexibility and rapid response when employed with proper planning and design. Advanced power electronic technologies are needed to unlock the full potential of these applications to contribute to modernization of the grid. A key development that is needed to support the growth of power electronic systems across the grid infrastructure is standardization of power electronics interfaces. A standardized interface would reduce the costs of integrating power electronic applications and enable them to improve many facets of grid functioning: system metrics of reliability, resiliency, power quality, security, economics, and efficiency. Adoption of power electronic building blocks for different grid applications so that they can be integrated into a coordinated control architecture would:

- Promote modular, scalable, interoperable systems at a lower cost than currently
- Reduce operation and maintenance costs
- Minimize impacts of load and source evolution and allow higher DER penetration by localizing generation and consumption without the need for capacity expansion or costly system upgrades
- Enable new grid paradigms (e.g., DC distribution) and seamlessly accommodate futuristic loads and sources
- Provide more flexibility and faster response times through power and energy management and advanced features like autonomous response to grid abnormalities
- Provide functions like black-start capability and grid-forming capability that can help mitigate the impact of catastrophic grid events

In addition, cyber hardening the design of power electronic components would help mitigate the risk of surface attacks on the grid.

To help identify synergies, gaps, and R&D opportunities for power electronics across the variety of applications and scenarios previously discussed, it would be useful to define a holistic framework. Advances in other power electronic components, subsystems, and system designs are also needed to maximize the capabilities that could be enabled by development in materials and components.

Requirements for the three main power electronic subsystems (power, controls and protection, and thermal management) are inter-related and depend on the system-level requirements. At the system level, connection voltage, power rating, and connection frequency are important parameters that affect system design and engineering. Research efforts could include a systemic analysis of parameters for each potential application of power electronics on the grid, to identify gaps and opportunities.

2.1.3.1 Materials and components research needs are described in the following subsections. Current Situation, Challenges, and Barriers

Generally, systems are composed of an interrelated hierarchy of materials, components, and

subsystems. The physical properties of materials affect the performance and design of components; various components are organized into subsystems to perform specific functions; and subsystems are organized, coordinated, and integrated with other ancillary components to build a system that meets the requirements of a specific application. Three critical subsystems are interdependent and responsible for the safe, reliable operation of a power electronics system: the power stage, the controls and protection system, and the thermal management system. R&D is needed at all levels of a power electronic system hierarchy, but advances in materials and components for semiconductor devices and modules have primarily driven the expanding scope of power electronic applications.

Power stage subsystem

The power stage subsystem is the core of a power electronic system and is responsible for physical manipulation of voltages and currents. Critical components include semiconductor devices, inductors, transformers, and capacitors. Research trends are favoring power electronic systems with higher power capacities and smaller footprints, which increases the electrical and thermal stresses on the power stage subsystem and associated components. Wide-bandgap (WBG) semiconductor devices are helping to increase system robustness by supporting higher voltages and improving thermal performance. WBG devices' faster switching frequencies also enable the use of smaller inductors and transformers, shrinking the power stage and increasing power density. However, other power-stage components are still limited in their high-temperature, high-voltage, and high-frequency performance.

- 1. Semiconductor devices**—HVDC and FACTS devices use higher voltage (e.g., 3.3–6.5 kilovolts [kV]) than other applications. Opportunities exist to increase device voltages (e.g., to 20 kV) for these high-power (megawatt) subsystems, which could reduce the number of devices needed and minimize the associated complexity. Opportunities also exist to develop low-parasitic packaging and techniques to address electromagnetic interference associated with high change in voltage over time. Research in WBG semiconductors (e.g., silicon carbide [SiC], gallium nitride) has led to the commercial availability of several low-voltage devices. Devices with voltages higher than 1.7 kV are also available as R&D prototypes, but challenges persist with manufacturing yields, wafer size, and process reliability. Although higher-voltage WBG devices are maturing, they lack the high current-carrying capability needed for high-power applications.
- 2. Capacitors**—Although AC and DC capacitors are both used in the power stage, DC link capacitors have significantly affected subsystem performance. HVDC applications may require unique solutions to achieve capacitors with current-carrying capacities at the megavolt level and higher (above 100 amps) without relying on series, stacking, or cascaded configurations. Synergies may be possible with other applications for advanced capacitors with low parasitics, especially equivalent series inductance, suitable for high-frequency systems (i.e., with WBG semiconductors).
- 3. Inductors and transformers**—The voltage, current, and frequency at which a device will operate are key drivers of the materials selection and design process for power electronic components. Filtering circuits are needed to manage common- and differential-mode currents, especially in high-power applications. Advances in transformers and inductors are a complex challenge because of the interactivity among performance characteristics. In general, a gap exists in core materials (e.g., those with good thermal and magnetic properties) suitable for high-frequency

and high-power applications. Compact, low-profile inductors and transformers for high-power density applications are also needed.

Control and protection subsystem

Subsystem components must be designed and coordinated to handle the operating environment (e.g., switching frequency, voltage, temperature) of a particular application. Trends toward faster switching frequencies enabled by WBG devices along with higher voltages and power levels introduce electromagnetic interference and the potential of high-energy faults (e.g., short circuits) that can damage or negatively impact other subsystems. Critical components include controllers (e.g., module, converter, switching logic), sensors that measure the state of the system (e.g., voltage, current, temperature), protection devices (e.g., contactors, circuit breakers, fuses) that respond and isolate parts of the power electronic system to prevent catastrophic failure, and auxiliary power supplies that support the entire subsystem.

1. **Module, converter, and switching logic controllers**—Use of WBG devices may change the overcurrent protection requirements of controllers. Currently, state-of-the-art commercial gate drivers for 1,200–1,700-volt silicon-carbide metal-oxide-semiconductor field-effect transistors have a response time of around 2 microseconds. With higher-voltage devices (10+ kV), the overcurrent protection requirements can be even more challenging because of increased short-circuit energy. Innovative overcurrent sensing techniques and high-speed analog/digital components that can work reliably in high-voltage environments are needed. Additionally, the fast-switching speed of WBG devices can cause false triggering of protection through parasitic coupling. Protection circuit design with ultra-low parasitic parameters and strong noise immunity continues to be a challenge. With the trend toward power-dense systems, controllers able to withstand high temperatures are also needed.
2. **Current and voltage sensors**—Advanced sensors are discussed in more detail in Section 2.3.
3. **Contactors, circuit breakers, and fuses**—The trend toward higher DC voltages to boost power ratings of power electronic systems introduces challenges for protection devices such as contactors and circuit breakers, especially with eliminating arcs without a zero-crossing. Use of WBG devices with higher switching frequencies will also require faster-acting protection devices. The trend toward more compact, power-dense power electronic systems may require new designs or different solutions. Additional details of protection devices are presented in Section 2.4.
4. **Auxiliary power supplies**—The efficiency, power density, and cost of auxiliary power supplies are important for meeting power electronic system design requirements. As power electronic systems trend toward higher voltages and increased power density, research is required to address isolation and other application requirements with new topologies. A potentially productive R&D focus would be on leveraging power electronic system advances for lower-power systems to serve as auxiliary power supplies for high-power applications.

Thermal management subsystem

The semiconductor components in thermal management subsystems are the primary drivers of the systems' design requirements. Typically, high-power semiconductors require active cooling elements, passive cooling elements (e.g., heat spreaders, heat sinks), and thermal interface materials (e.g., epoxy,

thermal grease, potting compounds, thermal foam). Increased temperatures can decrease the efficiency of power stages and affect operation of controllers and protection. Key components of the thermal management subsystem, discussed below, are the interfaces and packaging, the passive elements, and the active elements needed for heat exchange and removal.

1. **Interfaces and packaging**—Compared to traditional thermal greases, new thermal interface materials are significantly improving heat-transfer capabilities. Other advances include directly soldering or brazing the semiconductor device to the package or to the heat sink to avoid the thermal interface material altogether. New packaging techniques such as double-sided cooling are also being used to improve thermal management. Use of WBG devices that tolerate higher operating temperatures and have lower losses can reduce thermal management requirements. However, a holistic packaging solution is needed to manage parasitics from higher switching frequencies, higher voltages, and higher operating temperatures. Advances in interfaces and associated materials are also needed to better withstand thermal cycling effects and improve reliability, especially of WBG devices.
2. **Passive elements**—Passive elements facilitate heat transfer from the heat source to the coolant. With higher operating temperatures, the role of these elements becomes more critical. Current R&D focuses on improving conduction and spreading heat to enhance heat transfer. Innovative designs, new materials, and advanced manufacturing processes such as genetic algorithms may lead to more efficient heat sink designs, and mixed materials (copper/aluminum alloys) may provide greater design flexibility.
3. **Active elements**—Active elements work together to accelerate the convective cooling processes ultimately responsible for carrying heat away. Higher operating temperatures stress the current state of the art. Opportunities exist for new coolant materials, more robust and compact mechanical components, and tighter integration with passive elements and packaging design.

2.1.3.2 Technology and R&D Recommendations for Power Electronic Systems

- For power stage subsystems, application power can be increased through parallelization. Opportunities exist for power converter and circuit topologies that support scaling.
- High-voltage grid applications (e.g., HVDC, FACTS devices) pose unique challenges because of high-temperature and high-voltage environments, respectively. Continued research efforts should be made to develop solutions suitable for these extreme application environments. MMC-based VSCs have shown great potential.
- Advances in fundamental materials (e.g., magnetics, dielectrics) and component manufacturing are critical to improving cost and performance. Research should emphasize high-temperature, high-frequency performance.
- For WBG semiconductor devices, several research avenues are recommended:
 - Simplify designs with focus on making WBG devices useful to higher-power applications (HVDC)
 - Focus on improving thermal management, packaging, and reliability for high-current (e.g., 100+ amp) devices and modules

- Focus on advancing protection solutions, including DC breakers, faster-acting protection devices, and higher power over current protection schemes
- Develop controllers, sensors, and auxiliary power supplies
- Focus on packaging with novel materials, low parasitic designs, and immunity to electromagnetic interference and thermal cycling

2.1.4 Role of DOE

Table 4 summarizes the roles for DOE is well suited to play in supporting the recommended R&D for power electronics on the grid.

Table 4. DOE's Role in Supporting Recommended Power Electronics R&D and Addressing Barriers

R&D Technology Area	Recommended DOE Role
FACTS-based power-flow control devices	<ul style="list-style-type: none"> • Assist R&D for continuously improving the reliability and cost performance of FACTS technologies • Promote industry coordination and collaboration to facilitate field demonstrations of advanced FACTS devices • Assist transition to full-scale demonstrations and comprehensive field applications of hybrid low-cost devices • Coordinate development of testbeds or testing facilities • Support development of comprehensive simulation tools/frameworks to facilitate modeling and analysis of these technologies
Embedded HVDC systems	<ul style="list-style-type: none"> • Encourage and assist industry to expand field demonstrations of embedded HVDC systems • Facilitate collaborations between industry and academia for research on MTDC applications such as continent-level interconnection, renewable energy integration, and urban power grid uprating • Develop testbeds and testing facilities for validating new technologies used in HVDC applications and identifying viable technology routes • Hold workshops for utilities, regulatory bodies, and government to introduce the latest progress in MTDC technology
Power electronic building blocks for multiple applications	<ul style="list-style-type: none"> • Support development of power stage subsystem common architectures that can be used across multiple applications, as well as designs that integrate multiple functions into one device

2.1.5 R&D Recommendations Summary

The need for power-flow control arises from the fact that the generation-load balance must be maintained everywhere in the power grid at all times. The grid's highly interconnected topology, wide geographic distribution of transmission systems, and continuous variation in load demand at time scales from seconds to seasons complicate the application of any control process. Table 5 summarizes our power-flow control device R&D recommendations to improve grid efficiency, resilience, and reliability for the next 20 years.

Table 5. Power-Flow Control Devices R&D Recommendations Summary

R&D Technology Area	Recommended R&D Activities	R&D timeline
FACTS-based power-flow control devices	<ul style="list-style-type: none"> • Accelerate the maturation of advanced FACTS-based devices and emerging low-cost devices. Reduce cost and improve reliability of FACTS-based devices, which will be critical to justify their adoption. Expand field demonstrations and commercial applications of advanced FACTS-based devices, such as UPFC, which will help the technology iterate and evolve. • Develop capabilities for testing emerging power-flow control technologies in a lab environment that replicates field conditions. Because it is often impossible to test these devices on the real power grid, testbeds are necessary for the evolution of the technology. • Integrate iron-core-based FCLs to help relieve the impact of fault conditions on other power-flow control devices, enabling relaxation of design requirements. This will help lower the overall cost of power-flow control applications and improve their reliability. 	<ul style="list-style-type: none"> • Near term (1-5 years) because the R&D cycle of FACTS technologies is long, and emerging technologies are need test facilities where they can be validated.
Embedded HVDC systems	<ul style="list-style-type: none"> • Promote field demonstrations. Multi-terminal VSC-HVDC systems show great potential for use on the future grid, but it could be infeasible for industry alone to carry the technology to the next level of development and transition it to wide commercial availability. Field demonstrations are the key for fast develop of embedded HVDC technology. • Research advancements in Hybrid DC circuit breakers. Mechanical circuit breakers with current injection are considered a mature, cost-efficient technology. Pure solid-state breakers feature rapid operation but are limited by their interruption capabilities and cost. Breakthroughs in current and voltage capabilities could make these circuit breakers viable in HVDC applications. Hybrid concepts will be the most promising in the near future because of their balanced performance in operation speed, conduction loss, and interruption capability. • Research AC-to-DC conversion. Studies have shown its technical and economic benefits and that it might be more widely relevant than currently thought, but it has not drawn enough attention from policy makers. 	<ul style="list-style-type: none"> • Near term (1-5 years) because field demonstrations and commercial applications of embedded HVDC will have a significant impact on the development and deployment of the technology, and HVDC's use in U.S. has lagged behind the rate of adoption in other countries
Power electronic building blocks for multiple applications	<ul style="list-style-type: none"> • Power stage subsystem <ul style="list-style-type: none"> ○ MMC-based VSCs for transmission and submission power flow control systems. ○ Research advances in fundamental materials (e.g., magnetics, dielectrics) and their manufacturing into components (e.g., transformers, capacitors). ○ Develop high-voltage (20+ kV) WBG semiconductor devices for distribution and transmission scale power electronics systems. • Control and protection subsystem <ul style="list-style-type: none"> ○ Develop system protection for WBG semiconductor devices and higher-voltage (e.g., >1 kV) DC systems. ○ Develop innovations in controllers, sensors, and auxiliary power supplies to support a greater use of WBG semiconductor devices. • Thermal management <ul style="list-style-type: none"> ○ Develop new materials, more compact mechanical components, tighter integration with passives and 	<ul style="list-style-type: none"> • Near term (1-5 years)

R&D Technology Area	Recommended R&D Activities	R&D timeline
	packaging, and understanding of broader system interactions. ○ Package WBG semiconductor devices to address their high-frequency, high-temperature, and high-voltage operation.	

FACTS = flexible alternating current transmission; UPFC = unified power-flow controller; AC = alternating current; DC = direct current; HVDC = high-voltage direct current; MMC = modular multi-level converter; VSC = voltage source converter; FCL = fault current limiter; WBG = wide bandgap; kV = kilovolt

2.2 High-Power Delivery for Improved Resilience and Reliability

The U.S. electricity grid is divided into three regions known as “interconnections” that contain more than 15,000 generators operating synchronously at 60 Hertz within each interconnection. These generators send power through hundreds of thousands of miles of transmission lines that carry mostly AC electricity at high voltages (between 230 and 765 kV). The transmission system is configured as a network in which power can follow multiple paths from the generator to the distribution substation where the voltage is stepped down and sent into the distribution system for delivery to consumers. A few long-distance point-to-point lines use HVDC transmission between interconnections, which is done by converting AC to DC and then back to AC [46] [47].

The majority of the high-voltage transmission lines in the United States are installed overhead using poles and towers, but 0.6 percent of high-voltage transmission lines have been installed underground [48]. Underground high-voltage transmission lines have a life expectancy of 40+ years whereas overhead lines have a life expectancy of more than 80 years [48]. On a per-mile basis, underground cables are generally more expensive than overhead conductors but may make economic sense when other factors are considered. For example, underground cables are used where overhead lines are hard to locate, such as water crossings, and are increasingly considered advantageous for their resilience to wind and ice storms, reduced exposure to electromagnetic frequency, avoidance of visual pollution, and lower life-cycle costs [49]. Furthermore, underground cables can be used on shared right-of-way with other utilities, without impacting reliability concerns over use of common corridors [50].

A large proportion of transmission lines in the United States were constructed more than 60 years ago, and many are operating well beyond their design service life. Most of them are based on 1950s’ technology and were not engineered to meet today’s demand or to survive severe weather events [51] [46]. As a result of aging infrastructure, severe weather events, and vandalism, a total of 3,571 total outages, with an average duration of 49 minutes, were reported in the United States in 2015 [51]. Renewing or replacing aging assets will take decades and cost hundreds of billions of dollars [46].

As electric power demand increases and shifts in response to economic growth and demographic changes, more cables and conductors will be needed to increase the capacity and interconnectivity of the grid. Historically, installing new cables and conductors has been the preferred solution to increase transmission capacity. However, in response to an opposition from local communities and limited right-of-way, “re-conductoring” has emerged as a practical solution. Development of advanced cables and conductors that minimize losses or have high current-carrying capabilities would enable cost-effective re-conductoring and new installations. For example, the New York Transco Project will replace 80-year-

old 115-kV transmission structures by building, within the existing utility right-of-way, a 55-mile 345-kV overhead line with steel-supported aluminum conductors. This project will relieve congestion, improve grid resiliency and storm hardening, and unlock clean energy resources [34]. In some situations, capacity expansion through HVDC conversion may be the optimal solution, particularly when expansion is restricted to an existing right-of-way. However, with future improvements in the cost and performance of solid-state power electronics, conversion to HVDC could be attractive in a wider set of circumstances [42].

While high-voltage AC transmission remains the most common form of electricity transmission in the United States, HVDC transmission is considered a solution for distributing renewable energy (such as wind and solar) from remote areas where it is easily generated to more densely populated areas where electricity demand is high. The main applications of HVDC are bulk power transmission over long distances, submarine cable transmission, and asynchronous system interconnection [52]. Decisions about using HVDC vs. high-voltage AC are often based on the concept of the "break-even distance" where the savings gained by using HVDC lines offset the higher converter station costs required for operating HVDC lines. The break-even distance is in the range of 300 to 500 miles depending on several factors [50].

Unlike high-voltage AC cables, HVDC cables are not subject to a physical restriction limiting the distance or power level. This is especially true for underground or submarine cables [50]. Other advantages of HVDC include lighter, cheaper towers for DC cable because it can carry more power than AC cable, and it does not generate or absorb any reactive power, eliminating the need for reactive power compensation [53].

The United States, with its 20 HVDC transmission facilities, lags behind other countries on the deployment of HVDC lines. China and India are building 800-kV HVDC and 1,000-kV AC transmission lines along with the associated high-power infrastructure, and about 30 high-power HVDC projects are under construction in Europe, including many submarine cable connections to increase utilization of offshore wind power [46]. In the United States, plans to build the Plains and Eastern Clean Line, a 720-mile project that could have delivered 4 gigawatts of renewable power from the Oklahoma Panhandle region to states in the Southeast, were discontinued in 2019 [54] [55]. However, plans are ongoing to build the 349-mile SOO Green HVDC Link Iowa to northern Illinois, connecting wind-rich Midcontinent Independent System Operator to mid-Atlantic grid operator PJM. SOO Green is designed to avoid the problems that have dogged plans involving aboveground transmission lines. SOO Green will bury its HVDC cables underground and largely use existing rights of way owned by railroad companies [56]. Other plans for deployment of submarine HVDC lines include connecting future offshore wind farms to the grid [57].

The modernization and expansion of the electricity grid will require a comprehensive national vision based on consensus among the many stakeholders [46]. Specifically, state, regional, and national planning is needed to decide how the nation will deliver a significant fraction of its energy from renewables, especially wind and solar. It is important to mention that the technologies needed to modernize and to expand the transmission system are largely available now. However, further RD&D is

needed to reduce the cost of advanced technologies, and to attain further improvements that would be beneficial to encourage more rapid deployment of these technologies. Installing the technologies concurrently—that is, expanding and modernizing the power system simultaneously—would offer substantial cost savings. [46]. The federal government, in particular DOE, has a unique role to play in sponsoring RD&D activities, particularly to minimize the risk of these technologies for the risk-averse electric utility industry. Approximately 10 percent of the total power produced in the United States is lost in the process of delivering the power to the end user [49]. Investments in the RD&D projects discussed in the subsections below could reduce transmission losses by as much as 10–20 percent, improving the efficiency of the overall electricity system by about 1–2 percent, which would produce significant economic benefits [46].

According to the Energy Information Administration (EIA), electricity generated in the United States from renewable sources is expected to grow between 2020 and 2050 at a rate of ~ 44 terawatt-hours/year [58]. At the same time, over the next three decades, more than 140,000 miles of high-voltage transmission lines will come due for replacement [59]. This combination of factors creates a unique opportunity to make immediate RD&D investments to reduce the cost of advanced technologies for high power transmission that will enable improvements in the efficiency, durability, reliability, and resiliency of the future grid, resulting in significant economic and security benefits. Furthermore, there is some urgency to make these R&D investments now because the typical development cycle for many materials-based technologies can be as long as 20 years.

Such R&D investments should leverage the Materials Innovation Infrastructure, which is a framework of seamlessly integrated advanced modeling, data, and experimental tools. This framework aims to attain the Materials Genome vision of enabling the discovery, development, manufacturing, and deployment of advanced materials at least twice as fast as possible today, at a fraction of the cost [27]. These methodologies could serve as the cornerstone of activities to accelerate the design, development, and deployment of a new generation of materials-based technologies to improve the energy efficiency, performance, durability, and reliability of the electricity grid. DOE, and its Office of Electricity in particular, are uniquely positioned to lead these efforts because of their responsibility to ensure that the nation's electricity delivery system is secure, resilient, and reliable.

The faster these technologies become available, the sooner it will be possible to incorporate them in both the replacement and expansion of the current infrastructure and to begin reaping the benefits of greater efficiency and resilience. This is illustrated in Figure 1, which shows that implementing these technologies by 2025, which would be possible under an accelerated schedule starting today, would make them available just in time to have the greatest beneficial impact on the grid in 2040.

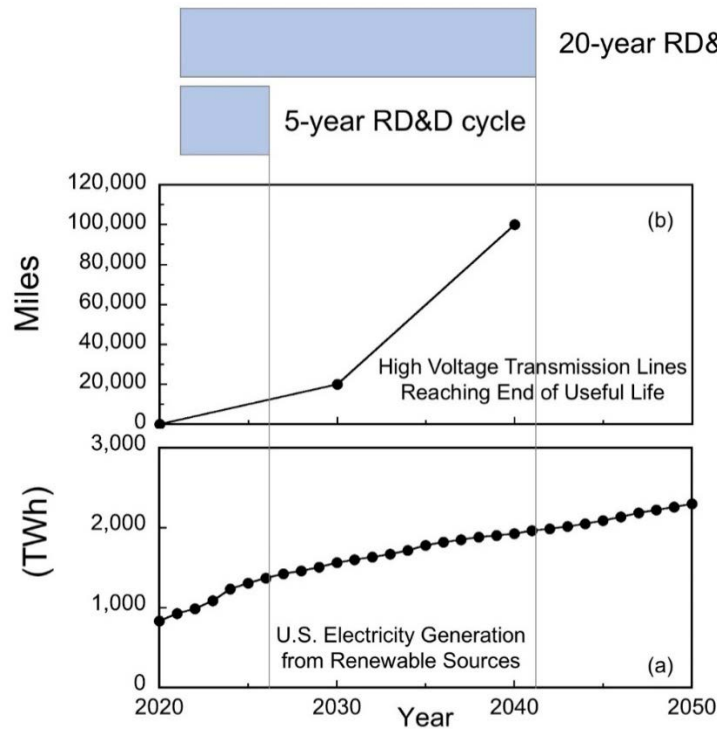


Figure 1. a) Projected electricity generated in the United States. from renewables [60]. (b) Number of miles of high-voltage transmission lines that will reach end of useful life [59].

This schematic illustrates the importance of initiating accelerated programs for R&D of technologies now, in order to have the greatest impact possible on the modernization of the electricity grid.

2.2.1 Conductors

2.2.1.1 Current Status, Challenges, and Barriers

Today, the most widely used configuration of high-voltage AC transmission lines consists of aluminum conductors strengthened by steel core wires [61]. Early versions of this technology were limited to operating temperatures up to 90° C. Above this temperature the conductive aluminum strands would anneal and lose strength. In the 1970s steel-supported aluminum conductors were designed and introduced to operate at temperatures above 200°C, which enabled them to deliver more power than the previous generation of conductors. Steel-supported aluminum conductors contained pre-annealed aluminum and improved galvanic coatings on the steel core wires. Dead-ends, splices and high-temperature oxidation inhibitors were introduced at the same time [62].

In subsequent years various classes of high-temperature low-sag conductors were developed. These include the 3M Company's composite-reinforced aluminum conductors, which replaced steel core wires with aluminum wires reinforced with ceramic fibers to improve conductivity and reduce sag and composite carbon fiber reinforced aluminum conductors that have a carbon or glass fiber-reinforced polymer matrix composite core. Like the other high-temperature low-sag conductors, composite carbon fiber reinforced aluminum conductors are capable of carrying more current than conventional

aluminum conductors strengthened by steel core wires, but at much lower operating temperatures and with reduced line losses. The coefficient of thermal expansion of the composite core is about 10 times lower than that of steel, so it offers excellent sag performance [62].

Interest has grown in improving the electrical conductivity of metals through a combination of alloying and thermomechanical treatments. For example, Cui et al. showed that the addition of boron combined with grain refinement is an effective method for improving the electrical conductivity and mechanical properties of aluminum-magnesium-silicon, aluminum-iron-silicon, and aluminum-iron-copper alloys [63].

Li and Hrtorstam demonstrated that the electrical and mechanical properties of alloys, such as copper, can be improved by reinforcing them with carbon nanotubes [29] [30].

Recently developed carbon nanomaterials, such as graphene and carbon nanotubes, have revealed enormous potential for applications such as electrical conductors [31]. For example, carbon nanomaterials' current-carrying capacity exceeds that of superconductors, and they are lightweight and have the highest values of specific strength and stiffness ever reported for any material [31]. They also exhibit high values of thermal conductivity and low thermal expansion, which are highly desirable to minimize sagging [31].

2.2.1.2 R&D Recommendations for Conductors

It is recommended that DOE support the development of alloys with improved electrical and mechanical properties. Such activities should use physics-based models and ML methods to discover and develop alloys with high strength and high values of specific electrical conductivity [27].

Research should be supported to develop methods and approaches for modifying the surface of metallic conductors to improve their oxidation and corrosion resistance while preserving low interfacial electrical resistance between conductors and connectors. This is a challenge because metallic alloys, such as those of aluminum, form a very protective thin oxide layer that is electrically insulating and, therefore, induces interfacial ohmic losses.

For metallic matrix composites, studies should be complemented by research to engineer the interface between the matrix and the carbon nanotubes to minimize electron scattering and losses, and to optimize the design of this class of composite materials—particularly by identifying the distribution of sizes of carbon nanotubes, their structure (e.g., single-wall vs. multi-wall), aspect ratio, concentration, and orientation with the goal of maximizing structural and electrical properties. Research is also needed to develop methods for cost-effective large-scale manufacturing of conductors and connectors using these materials.

Th special emphasis of research to develop carbon-based conductors should be on obtaining meso-scale structures that exhibit the inherent physical and mechanical properties of the nano-phased material. Research should also be supported to develop processes for manufacturing connectors to integrate carbon-based cables into electrical systems. Research should be supported to develop new

methods for large-scale manufacturing of carbon nanotubes and carbon nanotube-based conductors using low-cost abundant precursors, such as coal and natural gas.

Although the current technology and manufacturing readiness level of these technologies is low, it should be possible to accelerate the maturation of these technologies, in particular metallic matrix composites, over a relatively short period of time.

2.2.2 Superconductivity

2.2.2.1 Current Status, Challenges, and Barriers

After the revolutionary discovery of high-temperature superconductors in the 1980s, DOE made significant investments that culminated in the deployment of a superconducting sub-transmission-scale cable and the development of a pre-commercial, long-length, high-temperature, superconducting cable operating in a power transmission grid [36]. In 2014, the world's longest high-temperature superconducting cable was integrated into a power grid, connecting two substations in downtown Essen, German. This is a 1-kilometer, 10-kV (2,300-amp), high-temperature, superconducting cable cooled by liquid nitrogen [64]. Recently the European Union funded the Best Paths project to validate the operation of a 320-kV/3,000-megawatt superconducting cable based on magnesium diboride.

The widespread use of superconductors for high-voltage transmission applications has been hindered by their high operating costs, the complexity of their manufacturing, and issues related to ensuring the structural reliability of ceramic superconducting compounds [36].

2.2.2.2 R&D Recommendations for Superconductivity

Superconductivity continues to be a fertile field of discovery with the ultimate grand challenge being the discovery of room-temperature superconductivity. It is recommended that the DOE Office of Electricity continue monitoring the development of high-temperature superconductors, including the discovery of new compounds with critical temperatures near ambient conditions, which would negate the need for costly cryogenic equipment, which creates a major cost barrier to widespread deployment of high-temperature superconducting transmission lines today. New compounds with superconductive behavior at ambient conditions should be assessed for their viability for grid applications. For example, Mazzanti and Marzinotto recently reported that carbonaceous sulfur hydride compounds exhibit superconducting behavior at ambient conditions [65]. However, the exceedingly high pressures required to promote the transition to the superconducting state make use of these compounds impractical in the power grid environment. A predictive understanding of high-temperature superconductivity currently remains beyond our grasp as a scientific grand challenge, something that will require continuing support from DOE's Basic Energy Sciences Program in order to solve it [66].

2.2.3 Insulating Materials for HVDC cables

2.2.3.1 Current Status, Challenges, and Barriers

HVDC cables consist of an electrical conducting core (typically aluminum or copper), a semiconductor screen, an insulating sheath, and accessories [24] [25] [46]. HVDC cables are classified based on the type of dielectric material used for insulation. Types of cables include oil-filled, mass-impregnated, and extruded. Because cables insulated by multi-layer Kraft paper filled with pressurized oil require oil

feeding equipment and pose a risk of oil leakage, they have mostly been replaced by mass-impregnated cables [24], for which the main insulation is Kraft paper impregnated with a high-viscosity mineral oil compound.

In contrast to oil-filled and mass-impregnated cables, extruded HVDC cables rely on an extruded polymeric material, such as cross-linked polyethylene, as the main insulation. Extruded HVDC cables have become the technology of choice because they can withstand higher operating temperatures (up to 90°C) than oil-filled and mass-impregnated cables, which allows for more power to be carried for a given conductor cross-section. Furthermore, extruded HVDC cables are recyclable and can avoid environmental problems caused by oil leakage. The main drawback of extruded HVDC cables is the impact caused by space charge phenomena, which can distort the electric field distribution in the insulation, leading to accelerated aging and breakdown [26]. Although HVDC cables are considered a mature technology, further advances in performance and durability could be possible through the use of novel advanced materials, in particular using materials with higher electrical conductivity for the conductor and using more durable materials with improved dielectric properties for the insulating sheath.

Developments in insulating materials could increase the voltage level of high-voltage conductors. A limiting factor is that the total diameter of the cable (core + insulation) cannot exceed the maximum size needed for installation. The maximum diameter limits the thickness of the insulating material, which, in turn, determines the voltage rating. To increase voltage ratings without increasing the thickness of the insulating layer requires that the insulating material be able to withstand a stronger electrical field [67].

Data are lacking on electronic, mechanical, and dielectric properties of polymers [35]. However, the Materials Genome Initiative has enabled methodologies based on computational data generation, targeted synthesis, characterization, polymer fingerprinting, and ML predictive models; these methodologies and models can be used to accelerate the discovery of polymer dielectrics that can be used in energy technologies.

2.2.3.2 R&D Recommendations for Insulating Materials

DOE should support research that aims to discover polymeric materials that exhibit high dielectric breakdown strength and high environmental durability. Efforts should also focus on investigating the effect of adding nanoparticles of SiC, barium titanate (BaTiO_3), and zinc oxide (ZnO) to polymer matrix composites; these materials can reduce the impact of space charge. Specific areas of investigation would include determining the role of nanoparticle size distribution, concentration, and dispersion; the nature of the interface between a nanoparticle and polymeric matrix; and the resistance of the composite to moisture and temperature.

Those investigations should be complemented with multi-physics simulations to determine the response of HVDC cables to the simultaneous application of thermal and electromagnetic fields, structural loads, and environmental effects (e.g., wind, rain, snow). Those studies could be coupled with topology optimization techniques to identify geometrical features that could mitigate the effect of

space charge accumulation. As discussed above, the application of new methodologies for materials discovery and development could accelerate the maturation of technologies whose readiness is currently very low.

2.2.4 Connectors

2.2.4.1 Current Situation, Challenges, and Barriers

High-voltage connectors, which provide the necessary mechanical and electrical couplings between adjacent power line segments, are often identified as the weakest link in the electricity transmission network. As electrical loads on existing transmission lines have increased, the performance and integrity of aging connectors continue to degrade owing to accelerated surface oxidation from environmental exposure and elevated operating temperatures [49].

2.2.4.2 R&D Recommendations for Connectors

Opportunities to improve connectors include applied materials research to limit the surface oxidation rate and to devise advanced designs for enhanced mechanical and electrical connectivity. In addition, innovative low-cost sensing and monitoring techniques that can accurately provide information on the structural health of connectors can improve system reliability by allowing a shift to condition-based, rather than time-based, maintenance scheduling.

2.2.5 Wireless Power Transmission

2.2.5.1 Current Situation, Challenges, and Barriers

An alternative to the use of high-voltage conductors for power transmission is wireless power transmission, which entails converting electricity into electromagnetic radiation that can then be transmitted using an antenna, picked up by a receiving antenna, and distributed locally by conventional means. Interest in this technology has been renewed by recent developments in wireless charging of electric vehicles and consumer electronics devices although these applications rely on induction coupling and therefore are limited to operating over short distances.

The basis of wireless technology was established more than 120 years ago with the pioneering work of Hertz and Marconi. Today, it is pillar of the telecommunications industry; global wireless telecommunications using electromagnetic radiation with wavelengths in the range of millimeters to kilometers have been enabled by hundreds of geostationary and low-earth-orbit satellites that serve as relay stations [68]. However, telecommunications involve low transmission power levels.

In the wake of the energy crises of the 1970s, DOE established a Satellite Power System Project Office to assess the feasibility of beaming solar power to Earth based on a visionary concept proposed by Glaser [69]. This concept consists of using satellites to convert sunlight into electricity that would then be transmitted in the microwave region of the spectrum where minimum atmospheric absorption and scattering are encountered. On Earth, microwave power would be received by large rectifying antennas that would reconvert the beamed microwave power into electricity and feed it into a utility grid.

Reductions in in oil prices and unfavorable assessments by the National Research Council [70] and the Office of Technology Assessment [71] led to the termination of DOE's Satellite Power System program.

According to the Office of Technology Assessment, too little was known about the technical, environmental, and economic aspects of the technology to make a sound decision on whether to continue further development and deployment of space solar power. The Office of Technology Assessment report concluded that further research would be necessary before any decisions could be made. Interest in space solar power was renewed in the mid-1990s when the National Aeronautics and Space Administration (NASA) took a fresh look at the feasibility, technologies, costs, markets, and international public attitudes regarding this technology [72]. Since then, advances on several fronts have eliminated some of the technological and economic barriers to practical full-scale implementation of space solar power, as illustrated by recent activities in Europe [73] and in the United States, including data from the first in-orbit flight test of a solar-to-radio-frequency “sandwich module,” the construction of multiple in-orbit demonstrations planned for a 2023 launch that will demonstrate key technologies for space-based solar power, and demonstrations show that a 100-kW millimeter-wave power-beaming transmitter does not pose a risk to human life [74].

Electromagnetic radiation in the form of lasers with wavelengths in the vicinity of the visible portion of the spectrum have been successfully used for very-long wireless energy transmission as demonstrated by regular measurements of the distance between surfaces of the moon and Earth. Recent experiments performed by NASA in collaboration with French researchers have demonstrated the benefit of using infrared light for these measurements because it penetrates Earth’s atmosphere better than the visible green wavelength of light that scientists have traditionally used [75]. In recent years, the U.S. Department of Defense has invested in R&D on laser-based weapons. For example, in 2019 as part of its Power Transmitted Over Laser project, the Naval Research Laboratory demonstrated the operation of a long-range, power-beaming system consisting of two 13-foot-high towers 325 meters apart. One tower had a 2-kilowatt laser transmitter, and the other had a receiver of photovoltaics specially designed to be sensitive to the single color of light of the laser [76]. Also, under sponsorship of the U.S. Department of Defense, Lockheed Martin developed a spectrally beam-combined fiber laser that focuses a stream of multiple-kilowatt fiber lasers into a single high-quality beam with an electricity-to-laser light efficiency of up to 35% [77]. However, there are major obstacles to the use of laser-based systems for power transmission over long distances in electricity grid applications. Those include atmospheric scattering combined with obstructions to the line of sight between emitter and receiver, the potential hazard to human beings and animals, and the relatively low efficiency of generating a laser beam and reconverting it into electricity.

2.2.5.2 R&D Recommendations for Wireless Power Transmission

We recommend that the Office of Electricity monitor developments in wireless power transmission technologies both inside and outside the United States [78] and reassess potential future opportunities for using these technologies for long-distance power transmission.

At the same time, we recommend that the Office of Electricity fund a detailed technoeconomic analysis to identify the barriers and technical challenges for the deployment of microwave power transmission technology. Although it is unlikely that this technology will replace electrical conductors for long-distance power transfer, the technology could be used for post-disaster recovery if mobile transmitters

and receivers were deployed to temporarily close gaps between damaged or destroyed transmission and distribution lines [79].

2.2.6 Large Power Transformers

2.2.6.1 Current Situation, Challenges, and Barriers

Large power transformers (LPTs) are a key factor in grid resilience. Compared with the automation embedded on the low-voltage side of the system, there is comparatively little flexibility on the high-voltage side. Recent incidents and studies of physical attacks and threats on LPTs and the slow recovery process associated with fixing or replacing these damaged units have shown that rendering an LPT inoperable has major impact on the ability of the bulk electric system to serve load. It is not always possible to transport power “around” a damaged LPT by rerouting power flow through other substations or transmission lines.

Currently, 70% of LPTs are 25 years of age or older. The age of these components means that their ability to withstand physical stresses is degrading, potentially leading to higher failure rates [80]. LPTs cost millions of dollars, weigh 100 to 400 tons, are usually made to order, and can take up to 20 months to replace, depending on material availability. The lack of domestic manufacturing for these transformers, in particular 500-kV and 765-kV models, contributes to long lead times and presents an energy security challenge.

Because LPTs operate continuously and are generally heavily loaded, they must be designed to be exceedingly reliable and efficient. Although there are no moving parts in most transformers, the insulation around the conductors weakens as a result of chemical changes brought about by thermal aging. Of the several hundred LPT failures that were tracked in the United States between 1991 and 2010, most were due to failures in insulation, 28% were due to electrical disturbances (switching surges, voltage spikes, line faults, etc.), 13% were due to lightning strikes, and 9% were from insulation failure at normal voltages.

The North American Electric Reliability Corporation and Edison Electric Institute have instituted transformer sharing programs such as the Spare Equipment Database and the Spare Transformer Equipment Database, which encourage utilities to maintain and share a fleet of LPTs.

2.2.6.2 R&D Recommendations for Large Power Transformers

Even within utility transformer-sharing program(s), logistical challenges and location- and utility-specific design requirements (replacements have to match the design of the transformer being replaced) make LPT replacement a slow and expensive process. Modular transformers are designed to be moved quickly to replace damaged transformers, and uniformity of design would avoid the need for custom engineering and one-off transformer fabrication. One of the largest benefits of modular transformers is their transportability. Their use would eliminate the logistical issues associated with either procuring new LPTs or using existing spare LPTs. However, because of the physical size of existing LPTs, modular transformers normally are not an alternative replacement.

To be able to replace LPTs, modular transformers will need to be standardized, customizable, and developed or modified in a way that allows them to cascade (so that a large transformer can be replaced with several smaller modular transformers) to achieve the transformer capacity needed. Standardization of modular transformers is necessary so that they can be transported to any substation or utility without the need for redesign. A customizable component (possibly relying on specific power electronics) would need to allow for the modular unit's performance characteristics to meet the specific needs of any substation where it would be installed. Developing modular transformers that are capable of operating while ganged together (so that the connected transformers appear as one) would allow for these transformer systems to be deployed to meet the loss of any size of LPT. The DOE Office of Electricity in collaboration with DOE's Advanced Manufacturing Office are encouraged to lead partnerships with equipment manufacturers and utilities towards the development of modular transformers.

Other recommended research would focus on new insulation materials, low-loss magnetic core materials, electrical conductors for windings, and cooling of transformers, all of which would help increase their reliability. Joule heating in transformers typically accounts for losses in the range of 1%–2%, depending on the type and ratings of the transformer [80]. Advanced insulators and higher-quality dielectric materials, such as gases, could be utilized in transformer design to allow operations at higher temperatures and voltages, thus increasing transformer lifetime and reliability. Superconducting transformers have the potential to achieve high levels of efficiency. A transformer could be designed to take advantage of high-temperature superconducting materials, enabling it to be lighter and more compact and reducing its energy losses. Embedded sensors for real-time diagnostics and device monitoring can also improve performance and support preventative, just-in-time maintenance [80]. The DOE Office of Electricity is recommended to support the development of the aforementioned technologies.

2.2.7 Advanced Manufacturing

2.2.7.1 Current Situation, Challenges, and Barriers

Innovative AM technologies can enhance design and fabrication efficiencies, reduce life-cycle energy usage, and lower production costs. In particular, AM can substantially shorten prototyping and production times, accommodate innovative designs to enable multiple functionalities, and affect materials properties through process manipulation. AM encompasses techniques applicable across multiple material types and uses computer-rendered designs to produce a near-net-shape part, layer by layer.

AM has the potential to rapidly produce replacements for critical grid components in emergency scenarios, dramatically reducing grid down time. Furthermore, AM's many unique features offer opportunities to reduce design-to-product life cycle, to directly print raw materials into near-net-shape parts, and to manufacture unique materials and highly complex shapes to achieve superior performance.

Advances in AM technology and systems have enabled the fabrication of components from all classes of materials, including those required to meet the needs of the future grid.

Large-scale advanced manufacturing

- Metal big-area additive manufacturing
 - Metal big-area additive manufacturing is a wire-based metal technology suitable for fabricating large-scale three-dimensional objects. Initial systems offered a high deposition rate (3-5 pounds per hour) with complex tool-path planning. Maturation of this system with multiple weld heads achieves substantially higher build rates with the potential for compositional grading.
- Big-area additive manufacturing
 - Big-area additive manufacturing is an extrusion process that uses injection molding material for the feedstock. Commercialized systems are capable of delivering 100 pounds/hour of thermoplastic materials from pellet feedstock. Build volumes can exceed $20 \times 20 \times 10$ cubic feet.
- Sky big-area additive manufacturing
 - Sky big-area additive manufacturing is a cable-driven motion platform that is designed specifically around the requirements for deposition of large-scale structures. The target deposition rate for this system is 2.5 cubic yards per hour with a bead width of 2 inches and a layer height of 1 inch. The build volume is limited by the available footprint of the cable-drive system. This system can build structures $>50 \times 50 \times 50$ cubic feet.

Powder bed fusion

Powder bed fusion (PBF) achieves higher spatial precision than is achievable in large-scale systems, which allows PBF to fabricate more intricate components. However, the process is relatively slow compared to conventional techniques such as casting. Current state-of-the-art PBF systems are limited to a $3 \times 3 \times 3$ cubic foot build volume with low build rates.

Binder jet (slurry additive manufacturing)

Production line-scale printers can print build volumes containing a single or multiple parts nearing 70 cubic feet in total volume with build rates nearing 17 cubic feet per hour. Binder jet printing is a powder bed process that uses an inkjet head to deposit a binder to build objects from powdered media. Binder-jet manufacturing is well suited for fabricating metallic and ceramic-based components.

2.2.7.2 Summary of Advanced Manufacturing Techniques for Grid Applications

To realize the potential advantages of AM to help modernize the grid, it will be necessary to identify specific applications that could benefit the most from these novel technologies (for example, rapidly deployed temporary replacement parts during an emergency), and to target R&D investments to the development of processes and materials according to the application. Table 6 summarizes a series of grid applications for which appropriate existing AM techniques should be considered for near-term development.

Table 6. Maturation of Advanced Manufacturing (AM) for Grid Components

Class of Grid Component	Components	AM Technology
Structural	Transformer pressure vessel	Metal big-area AM
	Transmission towers	Big-area AM
	Substations	Sky big-area AM
Soft-magnetic	Transformers	PBF, Ultrasound AM
Conductors	Structural/electrical connectors	PBF, UAM
Dielectrics	Heat exchangers, heat sinks	PBF, UAM, binder jet
	Fiber -reinforced composites	Binder jet, polymeric extrusion
	Ceramic polymer composites	Polymer AM
	Bulk ceramics	Binder jet, slurry AM

PBF = powder bed fusion; UAM = Ultrasonic Additive Manufacturing

Opportunities for advanced manufacturing of grid components

Given the maturity of most advanced manufacturing technologies, there are numerous opportunities for innovation in the manufacture of grid components. Several key areas are outlined below, followed by a summary of recommendations for future R&D for AM for enhanced performance and resiliency of the future modernized grid.

Flexible component design for enhanced functionality

The layer-by-layer nature of AM allows grid component engineers to use advanced design techniques (such as topology optimization) to determine optimal component geometries for improved performance. In many cases, it will be possible to produce advantageous component designs that are not currently possible using traditional manufacturing techniques.

Materials selection and development for the future grid

The maturation of AM technologies presents an opportunity for the development of novel materials for next-generation grid components. Although AM technologies are not always well-suited for materials optimized for conventional processing, AM has enabled the fabrication of materials that are challenging to process. For example, researchers have fabricated high-silicon electrical steels (which are prohibitively difficult to process using conventional techniques) for soft-ferromagnetic applications using multiple AM techniques. Research in this area should focus on development of materials that take advantage of the AM's unique processing conditions to achieve properties and performance not available from conventional manufacturing.

Improving reliability and resiliency of grid components using embedded sensors

AM technologies offer an opportunity to utilize active sensing systems embedded in components, which would not be possible using conventional manufacturing methods. For example, the incorporation of piezoelectric micro-electromechanical system and fiber optic-based sensors during AM fabrication offers a streamlined approach to incorporating monitoring of the integrity of grid components during service. The integration of embedded sensors in big-area-AM-fabricated power transmission poles would enable smart routing of power through the grid during hazardous weather conditions.

Suggested demonstrations of AM-based grid components

Successful deployment of new AM technologies for rapid production of grid components can be dramatically accelerated through targeted R&D that focuses on demonstrating key application areas. Based on the current state-of-the-art in AM, we identify several near-term opportunities for demonstration components:

- **Power transmission poles.** Recent efforts have focused on exploring biologically based feedstocks. Rapid manufacture of bamboo reinforced bio-thermoplastics has been demonstrated, which could be used for manufacturing transmission and distribution poles and towers.
- **Bench-scale transformers.** Prototype 3.5- and 6-weight-percentage ferro-silicate benchtop scale transformer cores fabricated at ORNL using PBF-based AM demonstrate that AM is a viable process for fabricating transformer cores. The prototype used a complex design inspired by a Hilbert curve to produce a continuous thin-wall structure to minimize eddy current losses.
- **Heat sinks for next-generation power inverters.** In 2014, ORNL's Power Electronics and Electric Machines Group showcased a prototype designed (30-kW) power inverter that achieved higher power density than is commercially available. The prototype used an AM heat sink that was specifically designed to enable multiple functions: heat sink, structural support, and a conductive busbar. The multi-functional design enabled a full redesign of the inverter, which enhanced the functionality of the prototype.
- **High-voltage transmission line connectors.** AM provides additional degrees of freedom for designing and manufacturing connectors with unconventional geometries that could exhibit greater reliability and durability than current models. Connectors provide the necessary mechanical and electrical coupling between power-line segments. Power transmission can be limited by the connector-conductor contact resistance. Advances in connector design, surface modification to reduce oxidation, and improvements in contact strength and electrical resistance can enhance system performance. Integration of sensors to monitor connector conditions can also increase system reliability and reduce maintenance costs [80].
- **Soft magnetic materials.** Soft magnetic materials adapted for AM are another potential research avenue. Magnetics that are carefully "3D-printed" may exhibit lower parasitic losses than traditionally manufactured magnetics, among other benefits. The challenges of manufacturing of soft-magnetic materials have hindered their widespread adoption to date. Three-dimensional printing can address this issue if it enables the creation of finely tuned geometries and magnetic microstructures to reduce eddy current losses.

2.2.7.3 R&D Recommendations for Advanced Manufacturing

Ensuring grid resilience requires the use of state-of-the-art materials and manufacturing methods. Successful use of AM-based methods to produce grid components will first require extensive R&D to identify what components are best suited for AM as well as materials developments in alloy, ceramic, and polymeric systems that would enlarge the classes of components that are suitable for AM. Continued maturation of AM technologies has made the approach viable for higher-volume, low-margin applications. Table 7 summarizes our AM R&D recommendations to improve grid resilience and reliability for the next 20 years.

Table 7. Advanced Manufacturing (AM) R&D Recommendations Summary

R&D Technology Area	Recommended R&D
Technology maturation	<ul style="list-style-type: none"> • Large-volume PBF system development • Multi-slurry systems for ceramic AM • Advanced microstructure control for tailored properties
Materials development	<ul style="list-style-type: none"> • Targeted investment from associated DOE office (e.g., AMO, VTO, NE, BES) • Alloy design for advanced materials
Material and technology demonstration	<ul style="list-style-type: none"> • Selection of novel materials for use in grid components that are enabled by AM processes
Materials certification	<ul style="list-style-type: none"> • Industry standards for certifying AM components for use in the grid
Opportunities for advanced sensing and structural monitoring	<ul style="list-style-type: none"> • Incorporation of embedded sensors for monitoring component health and deep integration into a smart grid • Cyber risks of a mesh network of interconnected component sensors

PBF = powder bed fusion

In addition to advancements in manufacturing techniques, there are candidate innovative materials that could benefit the electricity delivery system. As highlighted in a DOE/ORNL [81] report, the following areas are still relevant needs for the future grid:

- **Diamond-based semiconductors.** Diamond-based power electronic circuits may provide superior thermal management and system performance compared with other technologies.
- **Nanocomposite soft magnetic materials.** These materials have the potential of having a disruptive impact in the field of passive power conversion for electrical transformers, by enabling low-loss operation when used at high frequencies.
- **Metal hydride alloys.** These alloys exhibit enhanced heat dissipation compared with standard metals used in transformer construction. Materials with a specific heat in the range of 1,200 to 3,000 kilojoules per kilogram could find broad application in thermal management.
- **Self-healing ceramics and polymers.** These materials could address technical challenges with electrical insulation in transformers. Ceramics or polymers, such as perovskites, are examples of materials that could recover quickly if damaged. Additionally, polymers with high thermal conductivity but low electrical conductivity could be explored for thermal management applications such as heat sinks.
- **Materials with decoupled electrical and thermal properties.** An isotropic material could be developed that orients electrical conduction and thermal conduction in different directions.
- **Heat pipes created from non-conducting composites.** Heat pipes are typically made from aluminum. Using non-conducting composites instead could result in a device that exhibits high heat transfer with no electrical conductivity.
- **Superhydrophobic materials and coatings.** Super hydrophobic materials can enhance reliability by preventing the buildup of ice and particulates on conductors. There is potential to develop anti-fouling and self-cleaning coatings.
- **“Smart” fault current-limiting devices.** Materials that alter their intrinsic properties when exposed to fault conditions could enhance the performance of protection systems.

- **Oil-improving additives.** When used as suspensions in transformer oil, these additives can increase the thermal conductivity of the oil, enhancing the lifetime and reliability of transformers.

It is recommended that DOE's Office of Electricity establish an RD&D program on materials and manufacturing, similar to programs established for other applied energy technologies within DOE, such as the Lightweighting and Propulsion Materials Programs in the Energy Efficiency and Renewable Energy office's Vehicle Technologies program, the High Performance Materials Program within the Fossil Energy Program, and the Office of Materials and Chemical Technologies within the Nuclear Energy Office. A materials and manufacturing program within the Office of Electricity would focus on translational research to help mature materials-based technologies that are relevant to the electricity grid and currently exhibit low technology and manufacturing readiness. Demonstration and deployment activities could take place in collaboration with industry and other stakeholders. It is also recommended that DOE institute a working group, similar to interagency working groups that have been established to facilitate information exchange in different areas of technology across the federal government that focuses on exchange of information about materials and manufacturing technologies. Such a group would increase the effectiveness of the DOE program offices by avoiding duplication, identifying gaps, and maximizing the success in RD&D on materials and manufacturing.

2.2.8 Role of DOE

Table 8 summarizes areas where DOE is well suited to support the recommended power electronics R&D efforts and address barriers.

Table 8. DOE's Role in Supporting the Recommended High-Power Delivery R&D and Addressing Barriers

R&D Technology Area	Recommended DOE Role
Conductors, ultra-conductors, and dielectric components	<ul style="list-style-type: none"> • Establish a materials and manufacturing program focused on components for modernizing the grid. Coordinate projects at DOE national laboratories, universities, and industry in a cooperative environment similar to DOE's energy innovation hubs. Engage stakeholders with competencies and expertise across the entire spectrum of technologies and manufacturing readiness levels in order to balance technology push and market pull, bridge scientific and technological gaps, and overcome barriers that can doom otherwise-promising technologies.
Superconductivity	<ul style="list-style-type: none"> • Monitor discoveries of compounds with critical temperature near ambient conditions and assess the feasibility of integrating these materials into grid applications.
Advanced manufacturing	<ul style="list-style-type: none"> • Coordinate and provide collaboration opportunities for development of industry standards for certifying components produced by advanced manufacturing for use on the grid. • Provide coordination and collaboration support within DOE to include the Offices of Electricity and Energy Efficiency and Renewable Energy.
Wireless power transfer	<ul style="list-style-type: none"> • Monitor developments in wireless power transmission technologies both inside and outside the United States [62] and re-assess, when appropriate, potential future opportunities for using these technologies for long-distance power transmission. • Fund a technoeconomic analysis to identify barriers to, and technical challenges for, deployment of microwave power transmission technologies. Although it is unlikely that this technology will replace electrical conductors for long-distance power transfer, the technology could be used for post-disaster recovery, e.g., by deploying mobile transmitters and receivers to temporarily close gaps between damaged or destroyed transmission and distribution lines [67].
Transformers	<ul style="list-style-type: none"> • Coordinate and promote collaboration among R&D organizations, industry, and utilities to standardize modular transformer components. Continue to develop R&D efforts to promote

R&D Technology Area	Recommended DOE Role
	<p>easily tunable/customizable transformers as an alternative to the long lead time for obtaining replacement models of large power transformers, which delays grid restoration.</p> <p>Support public-private partnerships to advance and accelerate testing and deployment of transformers, including modular transformers</p> <p>Promote collaboration with DOE's Advanced Manufacturing Office with equipment manufacturers and utilities towards the development of modular transformers</p> <p>Support development on new insulation materials, low-loss magnetic core materials, electrical conductors for windings, and cooling of transformers</p>

2.2.9 R&D Recommendations Summary

The aging transmission grid and its current reliance on less efficient technologies and manufacturing processes will limit the power sector's ability to address changing grid reliability, resilience, and architecture needs over the next 20 years. Table 9 summarizes the R&D recommendations for high-power delivery over long distances to improve grid resilience and reliability for the next 20 years.

Table 9. High-Power Delivery over Long Distances R&D Recommendations Summary

R&D Technology Area	Recommended R&D	R&D timeline
Electrical conductors	<ul style="list-style-type: none"> Accelerate development of alloys with improved electrical and mechanical properties using integrated computational materials science & engineering approach. Modify surface of metallic conductors to improve their oxidation and corrosion resistance while preserving low interfacial electrical resistance between conductors and connectors. Optimize engineering of interfaces between matrix and carbon nanotubes to minimize electron scattering and losses in metallic matrix composites. Optimize design of metallic matrix composites by determining the distribution of sizes of carbon nanotubes, their structure (e.g., single-wall vs. multi-wall), aspect ratio, concentration, and orientation to maximize structural and electrical properties. Develop carbon-based conductors, with emphasis on obtaining meso-scale structures that exhibit the inherent physical and mechanical properties of nano-phased materials. Develop processes for manufacturing connectors for integrating cables into electrical systems. 	<ul style="list-style-type: none"> Near term (1-5 years) based on the EIA Annual Energy Outlook 2020 and the number of miles of high-voltage transmission lines that will reach end of useful life in the next 10 to 20 years
Electrical insulators	<ul style="list-style-type: none"> Support discovery of polymeric materials that exhibit high dielectric breakdown strength and high environmental durability. Efforts should also focus on investigating the effect of adding nanoparticles of SiC,* BaTiO₃,* and ZnO* to polymer matrix composites because these compounds can reduce the impact of space charge. Specific areas of investigation would include determining the role of nanoparticle size distribution, concentration, and dispersion; investigating the nature of the interface between a nanoparticle and polymeric matrix; and increasing the resistance of the composite to moisture and temperature. Perform multi-physics simulations to determine the response of HVDC cables to the simultaneous application of thermal and electromagnetic fields, structural loads, and environmental effects (e.g., wind, rain, snow). Those studies could be coupled with topology optimization techniques to identify geometrical features that could mitigate the effect of space charge accumulation. 	<ul style="list-style-type: none"> Near term (1-5 years) based on the EIA Annual Energy Outlook 2020 and the number of miles of high-voltage transmission lines that will reach end of useful life in the next 10 to 20 years

R&D Technology Area	Recommended R&D	R&D timeline
Manufacturing processes	<ul style="list-style-type: none"> • Research use of metal and other materials to manufacture grid components, such as motors and transformers. • Adapt soft magnetic materials for advanced manufacturing. • Develop structural composites that use lightweight, high-strength, failure-proof structural materials to reduce weight and installation costs while enhancing reliability. • Develop methods for cost-effective large-scale manufacturing of conductors and connectors. • Develop cost-effective large-scale manufacturing of conductors and connectors using metallic matrix composite materials with improved electrical and mechanical properties. • Develop processes for manufacturing carbon nanotubes and carbon nanotube-based conductors using low-cost abundant precursors, such as coal and natural gas, and processes for manufacturing connectors for carbon nanotubes and carbon nanotube-based conductors into electrical systems. 	<ul style="list-style-type: none"> • Near term (1-5 years) for developing advanced materials and manufacturing methods that help accommodate the end of useful life of existing infrastructure
Transformers	<ul style="list-style-type: none"> • Modular transformers <ul style="list-style-type: none"> ○ Standardize modular transformers so that they can be transported to any substation or utility without the need for redesign. ○ Develop customized component (possibly using specific power electronics) that allows for a modular transformer's performance characteristics to meet the specific needs of any particular installation. 	<ul style="list-style-type: none"> • Near-term (1-5 years), focused on power electronics and need for ability to deploy transformers quickly in response to an event

EIA = Energy Information Administration; SiC = silicon carbide; BaTiO₃ = barium titanate; ZnO = zinc oxide

2.3 Advanced Sensors

The operation of the electric energy system relies heavily on grid measurements. Thus, grid visibility is vital to system reliability, resiliency, and security. System monitoring and access to system data are foundational for situational awareness, operations decision making, and long-term planning. This section focuses on grid monitoring needs. Three monitoring topics critical to ensuring a safe, reliable electric grid are high-fidelity sensors, asset monitoring, and advanced timing systems. Within each topic area, we discuss the state of the art, technical challenges, and R&D efforts that need DOE's support in the next two decades.

Through a partnership with industry and DOE, the North American SynchroPhasor Initiative has been improving power system reliability and visibility by fostering the use of synchrophasor technology for wide-area measurement and control. The efforts have greatly improved the situational awareness and grid visibility of the transmission system during the past two decades. However, integration of advanced sensors in power system control rooms has been slow. R&D efforts are needed to improve the reliability of sensors and the availability of their measurements as well as to reduce installation and integration costs. Policy and regulatory action can help accelerate adoption of mature sensor technologies. This section focuses on advanced grid sensors for the transmission system.

2.3.1.1 *Synchronized Measurements*

Currently, transmission control centers are supported mainly by supervisory control and data acquisition (SCADA) systems, which use devices called remote terminal units (RTUs) located at generators and substations to measure and report the status of circuit breakers, voltage, current, and power. The typical response time for SCADA systems is several seconds. The measurements are not accurately time synchronized. By contrast, wide-area monitoring systems are a revolutionary technology that can report system status (voltage, current, frequency, phase angle, power) much more frequently (60 times per second or more), and all measurements can be time synchronized using the global positioning system (GPS). This enables characterization of system operation and dynamics over a wide area. Funded by the American Recovery and Reinvestment Act of 2009, more than 1,000 phasor measurement units (PMUs) have been deployed on the U.S. power grid during the past decade. Many software applications have been developed to aggregate and analyze the PMU data, greatly enhancing situational awareness of the transmission system. Wide-area monitoring systems have been bringing unprecedented situational awareness capability to control centers; these systems are expected to continue to play a key role in bulk system operation and planning.

However, wide-area monitoring systems require significant advancements before they can be fully integrated into day-to-day system operation, particularly for real-time system control and protection. This section first discusses the challenges of current synchronized measurements and some possible solutions and then focuses on the future of synchronized measurements in the next two decades in terms of measurement intelligence, multi-function measurement, and ubiquitous measurement.

Current Situation, Challenges, and Barriers

Timing synchronization: Timing is an essential component of synchronized measurements. Since its invention, the GPS has been the dominant timing source for synchronized measurements because of its easy access and low cost. However, various uncontrollable and unpredictable factors (e.g., atmospheric disturbances, weather change, solar activity) can cause GPS receivers to lose timing, which is a very common problem of PMUs deployed on the U.S. grid. Synchronized measurements are useless without accurate timing. In addition, GPS signals are weak and are prone to spoofing. Manipulated timing poses significant risks to synchronized measurements-based applications, particularly real-time system control and protection applications. Therefore, addressing issues that can interfere with accurate timing of synchronized measurements is critical for this technology to be widely adopted in control rooms. Some alternatives to GPS have shown promising experimental results. A detailed discussion of these advanced timing sources is presented in Section 2.3.3. Although preliminary experiments have demonstrated the performance of some timing technologies, deployment of these technologies for synchronized measurements on the grid would need DOE's investment in long-term performance demonstrations, system-level integration of multiple time sources, and benefit-cost analysis for key monitoring sites.

Measurement applicability: Another challenge of synchronized measurements is that the measurement performance (accuracy, latency, dynamic response, fault-tolerance capability) is not applications-oriented. Synchronized measurement was invented before it was fully understood how the data would be applied and therefore what requirements the data would need to meet. Wide-area monitoring systems include potential transformers (PTs)/current transformers (CTs), PMUs, a communication network, data storage, and other components; each component could introduce measurement uncertainty, delay, or loss. For example, during system transient events, it is unknown what measurement errors are made by PMUs, which means that use of PMU data in system protection during system transients need carefully designed. Even the PMU could pass the Institute of Electrical and Electronics Engineers (IEEE) standard, the measurement behaviors of PMUs during system transient faults are hardly predictable. Clearly defining the measurement requirements of each application that depends on synchronized measurements is key to R&D efforts on this technology and to its wide adoption in control rooms. Some grid applications, such as protection, require less-accurate but high-rate and low-latency measurements whereas applications such as dynamic state estimators will require high-accuracy measurements. In short, the requirements for synchronized measurements need to be defined quantitatively to guide R&D on synchronized measurement technologies.

Synchronized measurements will continue to contribute to situational awareness of U.S. transmission systems during the next two decades. However, without DOE's support and investment, this technology will advance slowly. Overcoming current challenges will require large R&D investment and close collaboration among utilities, industry, and national laboratories, both of which DOE is ideally situated to facilitate.

R&D Recommendations for Synchronized Measurement

Measurement intelligence

Measurement Algorithm Intelligence: The increasing penetration of renewable energy and power inverters on the grid will result in a dynamically changing energy system in which voltage and current could change dramatically in a short time. This has already created difficulties with existing synchronized measurement systems. From the methods point of view, a longer estimation window is required to obtain accurate measurements of steady-state voltage/current waveforms whereas a shorter measurement window is preferred for dynamic voltage/current waveforms. The existing fixed-window approach could result in significant measurement errors in a rapidly varying environment. Additionally, when system transient faults occur, voltage/current waveforms can be highly distorted (e.g., waveform discontinuities, high-frequency interference), causing large, unpredictable measurement errors.

A promising solution is to develop measurement algorithm intelligence enabling a measurement device to intelligently detect the change in the environment and dynamically adjust its measurement algorithm in real time to provide optimal data for the conditions at the instant the measurement is taken. For example, the algorithm intelligence could detect rapidly varying system dynamics or faults and adjust the algorithm to a shorter measurement window with a high-order fitting model, and then gradually readjust to a normal measurement algorithm as system dynamics or faults decay. More importantly, when grid voltage or current waveforms are highly distorted and an accurate measurement cannot be estimated, the measurement report should notify users (system operators or grid devices) that the measurements are inaccurate.

There are two main approaches to developing measurement algorithm intelligence. The first approach is the traditional model-based method, in which one can develop a mathematical model for the voltage and current waveforms and use threshold(s) to categorize system events. This work is challenging because power systems are very complex, and generalizing voltage/currents mathematically is difficult, particularly during system transient faults. The second method is to use AI, which has shown its advantages in many other areas. There are two main challenges of developing measurement algorithm intelligence using deep learning. First, the computation cost of executing AI on a grid device could be high, resulting in high device costs. However, because AI has advanced very quickly in recent years, it seems likely that this challenge can be easily overcome. The second challenge is the availability of data for training models such as neural networks. A useful deep learning model requires substantial data. The power system generates a huge amount of data every day; however, for many reasons, sharing the data among different organizations is difficult. Developing a strategy for easy sharing of data among different organizations (utilities, industry, national laboratories, academia) is critical to not only developing measurement intelligence but also other AI applications in power systems. DOE could play a vital role in facilitating this collaboration.

Distribution Measurement Intelligence: In addition to measurement algorithm intelligence, future measurement intelligence could be applied at the monitoring the system level. Grid monitors at different locations could form a distributed monitoring network to enhance measurement dimensionality, security, availability, and reliability. For example, when one device produces suspect

data or exhibits suspicious behavior (e.g., cyber-attack or device malfunctions), nearby devices could vote to flag the device and report it to the central system so that it is excluded from the monitoring system. The monitoring network could reconfigure, and a normal device nearby could step in to replace the problem device. The distributed measurements system could also be designed to handle problems such as communication failures, bad measurements, and so on. Each device should be able to communicate bidirectionally with other devices in the monitor cluster and produce the best measurements from a system point of view. For example, a monitor could change its measurement functions to measure power quality when it detects power quality issues in a local measurement environment and then change back to normal synchrophasor measurements when the power quality issues subside. Overall, monitors working in a cluster provide improved measurement availability, reliability, safety, and measurement versatility compared to devices working in isolation.

Multi-function Measurement Devices

Encompassing multiple functions in a single device is gradually being done today. Most current synchronized measurement devices focus only on phasor measurements, including voltage/current magnitude, phase angle, power, frequency, and rate change of frequency. With advances in hardware (microprocessors, field-programmable gate arrays), communication bandwidth, and cloud computing, future synchronized measurement devices could not only perform synchrophasor measurements, but also many other grid measurement functions such as point-on-wave (instantaneous voltage and current waveform) measurements, transient fault and dynamics recording, and power quality measurements. Synchronized point-on-wave measurements are emerging as part of power system analysis. These measurements allow for many types of assessments, such as DER modeling, power quality analysis, events detection and location, and disturbance classification. Collection of point-on-wave data could be in a continuous stream or only when triggered by an event. The event-triggered measurements would entail lower communication bandwidth and storage costs whereas continuous streaming would require high bandwidth and storage costs. Because point-on-wave measurements have a high sampling rate and therefore could generate large volumes of data, technologies need to be developed to compress the data for both transfer and storage.

Ubiquitous Measurement

Synchronized measurements are mainly available in high-cost grid devices such as PMUs and relays. However, with the expected advancements in hardware (microprocessors), communication networks, and timing during the next two decades, synchronized measurements could become a standard, embedded measurement function in many grid devices such as reclosers, disconnectors, solar inverters, smart meters, and other new devices that do not exist yet. R&D efforts toward ubiquitous measurement should focus on extremely low-computational-cost measurement methods, which will be critical for integrating synchronized measurements using low-cost edge computing devices. Synchronized measurements on the grid edge would not only tremendously increase grid visibility, but also enable these devices actively to participate in grid operations.

DOE's role in the abovementioned R&D recommendations is vital. For example, if measurement instrument manufacturers need to meet the measurement performance required by the Institute of Electrical and Electronics Engineers/International Electrotechnical Commission PMU standards, R&D in

these new areas may not produce significant profitability in near term, creating a disincentive for private investment.

R&D activities critical for the advances needed in synchronized measurement over the next two decades should focus on development of:

- GPS-independent/alternative timing technologies for synchronized measurements to enhance data quality
- Application-driven synchronized measurement technologies to enable the overall monitoring system performance to meet the needs of power system applications
- Measurement intelligence, including measurement algorithms intelligence and distributed measurement intelligence, to enhance measurement accuracy, reliability, availability, security, and versatility
- Multiple measurement functions integrated into one device, including synchronized measurements, point-on-wave measurements, power quality measurements, transients, and dynamics recording
- Extremely low-computational-cost measurement methods allowing ubiquitous synchronized measurements in various grid equipment pieces

2.3.1.2 Optical Monitoring Systems

Current Situation, Challenges, and Barriers

High-fidelity voltage and current transducers play an essential role in improving grid reliability and resilience by providing instantaneous voltage and current waveform measurements. Conventional electromagnetic PTs and CTs are widely installed to provide a measurement interface for grid monitoring devices. Unfortunately, these widely deployed magnetic-core-based PTs/CTs have inherent weaknesses, such as magnetic saturation, electromagnetic interference sensitivity, and poor linearity.

Advantage of Optical Transducers

Fiber-optic sensors are an emerging technology for physical parameter measurement and are a promising technology for measuring power grid voltage and current without the inherent weaknesses of conventional transducers. Optical sensors could provide highly accurate measurements in a wide frequency range that is outside of the capabilities of electromagnetic CTs and PTs. Optical sensors' measurement accuracy could exceed that of metering class PTs/CTs, and the improved accuracy could benefit many power system applications such as state estimation, power-flow monitoring, system modeling, and fault location. Furthermore, optical sensors have a wider dynamic range than electromagnetic PTs/CTs, enabling the capture of high-frequency system transients. Optical sensors are also immune to DC offsets and are not subject to the "magnetic saturation" that PTs/CTs experience. This means that optical sensors could provide accurate measurements during transient faults that contain DC decay. Additionally, optical sensors are immune to electromagnetic interference, so they can provide high fidelity in harsh electromagnetic environments.

In addition to measuring voltage and current, optical sensors can integrate parameters such as pressure, vibration, acoustics, and temperature into one platform and offer the flexibility of field deployment. In the context of an increasing occurrence of arcing-induced wildfires in the United States, which is, in turn, resulting from a combination of aging power delivery equipment and climate change, an optical monitoring platform would offer new possibilities to detect arcing faults and reduce the chance of wildfires.

In addition to measurement performance, optical sensors have other advantages. They do not require oil and SF-6. They also replace copper cable with a fiber optic link to the control center, eliminating a path for voltage and current surges that can be hazardous to personnel and equipment. Even more important, optical CTs eliminate the human hazard caused by open-circuited CT secondaries.

R&D Recommendations for Optical Sensors

The R&D activities recommended for optical sensors below assume that during the next two decades, traditional magnetic PTs/CTs will not improve significantly to address their disadvantages, which will likely be true because some of those disadvantages are determined by the materials of which the devices are made.

An optical sensor characterization platform needs to be developed for comprehensively evaluating the performance of optical devices under various grid operation conditions. The performance of optical sensors needs to be thoroughly tested and compared with the performance of traditional PTs/CTs to document optical sensors' advantages. Long-term field demonstration and testing of optical devices are needed to document field performance. Optical sensors can be installed at substations and integrated with devices such as relays, power quality analyzers, and PMUs. A communication interface is needed to integrate optical sensors with existing grid legacy control-center devices that are designed to accept conventional 120-volt/5-amp inputs. Digital communication between protection and control devices (IEC 61850) aims to solve this problem but is being developed at a slow pace. DOE's investment in this R&D along with utilities' participation and feedback will be critical for success. Additionally, R&D efforts should aim to reduce the cost of optical devices so that they are competitive with traditional devices. We recommend that DOE initiate a pilot project to demonstrate the advantages of optical devices over traditional devices. The project could employ a multiple-parameters grid monitoring system containing optical devices to address high-impact real-world problems that industry and utility face, such as wildfire detection and mitigation; and partial discharge detection and location from a wide range of substation apparatus including LPT, bushings, and load tap changers.

2.3.2 Asset Monitoring

Efficient operation and resilience of smart grids depend on their ability to anticipate, absorb, and/or rapidly recover from disruptive events. Asset monitoring related to disruptions is challenging because of the geographical extent of the transmission system and the system's typical failure modes. Examples of conditions that need to be monitored include conductor breaks, connector splice failures, dynamic line ratings, high-impedance faults, insulator mechanical degradation, dry band formation and arcing, leakage currents, switch mechanical degradation, circuit breaker mechanical degradation, switchgear

humidity, capacitor degradation, oil degradation in bushings and transformers, and transformer winding insulation degradation.

Embedded sensing, advanced sensing, and measurement techniques will be key to real-time load and power monitoring of future smart grids. As the internet of things industry and hybrid electronics technology evolve, an opportunity exists to pursue sensor systems with self-identification, self-localization, self-awareness, self-diagnostics, and self-calibration capabilities.

This section highlights R&D recommendations to DOE, related to foundational sensor platforms that can transform the future grid. We highlight embedded systems, advances in materials and manufacturing systems, and flexible hybrid electronics, which (if successfully developed) will be able to create systems capable of monitoring many of the grid assets highlighted previously and will support the current DOE multi-year Advanced Sensor and Data Analytics plan.

2.3.2.1 Current Situation, Challenges, and Barriers

Numerous efforts have been made in recent years to develop sensors for monitoring transmission assets. In the overwhelming majority of cases, the new monitoring technologies were designed independently of the asset, had to be customized for installation, and did not operate seamlessly with SCADA systems. Not surprisingly, the commercial adoption rate of these devices has been extremely low. More clearly identifying the causes for these low adoption rates and more clearly defining the challenges associated with successful adoption of asset-monitoring technologies should be a key focus of future R&D efforts. An understanding of these past experiences and a definition of barriers will enable identification of technology development and implementation needs that, if addressed, are more likely to result in commercial adoption of asset-monitoring technologies.

2.3.2.2 R&D Recommendations for Asset Monitoring

One hypothesis for the low adoption rates of research-grade asset monitoring technologies is the ad hoc nature of sensor development and installation. The total independence of the design of the asset-monitoring technology significantly increases the likelihood that monitoring performance will be poor, sensor installation will be a burden, and sensor operation will add complexity to current operations. To address these challenges, we suggest R&D on embedded sensing for asset monitoring.

Embedded sensing in this context refers to more than merely incorporating the sensing device into the asset. It is based on a system engineering approach to sensor and asset design and use. Systems engineering is an interdisciplinary method that considers the design, integration, and operation of complex systems over their life cycles from an engineering perspective. This comprehensive design approach enhances the robustness and reliability of the resulting system. In the case of grid assets and their monitoring systems, using a system engineering approach would increase the likelihood that the monitoring system will meet all design and operating requirements.

In addition to system engineering of the asset and sensor, a key element of future embedded sensing efforts should be seamless integration of the monitoring technology and the asset that takes advantage of emerging manufacturing methods. The co-design and seamless integration of a sensing method and

an asset structure has three primary benefits: (1) more precise and repeatable measurements of asset performance resulting from the physical fine-tuning of the structure and sensing method, (2) reduction or elimination of labor and the possibility of error associated with field installation of sensors, and (3) simplified operation of asset monitoring technology and interpretation of data resulting from optimized design of the asset structure and sensing approach. Example manufacturing methods that can be applied toward this end are AM and direct-write printing using functional materials. System engineering of assets and monitoring methods using these advanced manufacturing methods will have to consider sensor powering, on-board signal processing, telemetry, and integration with relevant data acquisition systems used by utilities.

In addition to embedded sensing, two other important area of focus are advances in materials and manufacturing techniques and the drive toward co-integrated diverse technology concepts. This combination is pushing the cost/performance ratio of current sensor technology and, at the same time, offering new possibilities for multi-functionality provided an integrated platform of sensors and components. The recent rapid progress in wireless communications and microsystems has enabled the realization of low-cost, miniaturized wireless devices for sensing, measurement, and data collection. Wireless sensor networks have tremendous potential to enable the design of multi-functional, long-lasting sensor platforms that can help meet grid resilience targets through real-time monitoring of the grid environment, structural health, power flow, and energy management.

Wireless networking capabilities offer unprecedented opportunities for instrumenting and controlling smart grid infrastructure, and wireless technology is a flexible, cost-effective solution. However, wireless design demands the development of low-power sensors that can make the energy harvesting and storage technologies accessible for long-term (several years') autonomous operation on sensor platforms. Just as low-cost, high-performance sensors are critical to meet the requirements of grid technology, sensor reliability and capability of being integrated with other sensors, communication components, and signal processing circuitry on a system platform are critical to achieve the desired operational mode. Sensor identification and development must consider system-level aspects of design and interfaces for autonomous initiation, data processing, self-calibration, and energy management for self-sustained operation. A successful technology transfer to manufacturing and market acceptance will depend on the synergy between the system functionality and manufacturing techniques. Because advanced materials, high-volume manufacturing techniques, and system integration possibilities are evolving at a rapid pace, the complete sensor platform design strategy should be evaluated regularly for the interplay of cost, performance, functionality, and expected benefits.

Flexible hybrid electronics and internet-of-things technology are poised to add an unprecedented level of connectivity to every aspect of grid infrastructure and to provide real-time remote monitoring with almost no human interaction. Flexible hybrid electronics technology also has the potential to bring together design, fabrication, and packaging in a single manufacturing set-up. Next-generation multifunctional sensor platforms can be implemented by co-integration of the following components: (1) multi-modal sensors, (2) active/passive circuit elements, (3) antenna, (4) radio frequency electronics, and (5) photovoltaic cells. The integrated sensor system approach brings together functional sensor elements on low-cost substrates: multi-parameter detection, data processing, wireless communication,

and energy harvesting. Aligning with the goals of smart grid technology, wireless protocols are a key focus of developers. The internet of things platforms offers the integration flexibility to meet the wireless range, data rate, energy consumption, and security requirements of the target application. Internet of things technologies are radically changing the way sensors are used. Combining a set of sensors and a communication network reduces huge volumes of generated data into actionable information. For successful integration into internet-of-things platforms, the sensor technology R&D must address cost, footprint, data processing, power consumption, self-calibration, and maintenance requirements.

Internet-of-things platforms are being shaped by a broad range of technologies such as sensors, wireless communication, battery storage, photovoltaics, and data analytics, employing low-cost manufacturing and hybrid integration approaches. A significant opportunity exists to bring together innovative materials, process technology, device designs, and system integration ideas to realize multifunctional platforms. Involving domain experts from these technology sectors in R&D efforts will help establish a clear understanding of existing technologies, technology gaps, and market opportunities targeting both short- and long-term roadmaps. Innovations and advanced technologies are critical for global competitiveness and leadership. An R&D effort that can expand the knowledge of experts from one domain to other domains will be instrumental in attracting industry participation. In addition to the benefits of connecting with innovative research strategy and intellectual resources, we believe industry partners would be responsive to a smart grid research program that integrates the elements of advanced sensors / systems and technology-to-market pilots. Advanced research and technology development efforts on innovative sensors and internet-of-things platforms that will offer real-time insight into every generation, transmission, and distribution asset will enable industrial partners to connect with the Smart Grid Sensors Market, which is projected to reach \$1,221.6 million by 2027 (compound annual growth rate of 18.3% from 2020 to 2027) [82].

As an application case, low-cost sensors are required to monitor oil-insulated transformers, which are among utilities' most expensive pieces of equipment. Dissolved gas levels in transformer oil can indicate the existence of a fault, so monitoring changes in these levels could improve transformer maintenance. Continuous monitoring of dissolved gases along with wireless communication of the sensor data at low power and low cost are essential to realize a practical transformer fault diagnosis system. By placing intelligence at the transformer, utilities can run computational algorithms, analyses, and other health-monitoring functions that can simultaneously observe the use of the electricity on the "secondary side" and distribution visibility to the "high side." Without SCADA extending to transformers or other investments, utilities could benefit from this added operational visibility of their networks, wires, and customers.

DLR is another key transmission-line status that could benefit from monitoring. DLR monitoring could help operators keep the line power flow below the transmission-line thermal rating while also helping to maximize the transmission line power capacity. Before the invention of DLR, line thermal ratings were usually static. DLR was invented to obtain additional transmission-line thermal capacity by estimating capacity in real time. DLR uses both real-time air temperature and effective perpendicular wind speed for monitoring thermal rating. DLR is a relatively mature technology, but its adoption has

been slower in the United States than in many other countries. Working with utilities and national laboratories, DOE could play a vital role in facilitating commercialization of DLR. One of the efforts that is recommended for DOE focus is working closely with utilities to identify high-value applications of DLR to system operations.

Future DLR should not only estimate the current overhead line rating, but also have the capability to predict line rating over a wide range of time frames from an hour ahead to a day ahead, which could be achieved with AI. Very-short-term DLR forecasts could help operators manage N-1 post-contingency loads, and accurate day-ahead predictions are a powerful tool for markets that need day-ahead line capacity predictions. From the R&D perspective, accurate DLR prediction is challenging because of the complexity of weather prediction. Temperature prediction is relatively simpler, but accurate, high-resolution wind prediction is challenging, particularly for low wind speeds. Recent advancements in AI could play a vital role in accurate weather prediction during the next two decades, contributing to higher-accuracy DLR with accurate prediction capability. In addition to estimating thermal limits, DLR can also be applied to clearance-limited lines. For some utility designs and many conductor types, clearance limits, rather than thermal limits, are the prominent constraint.

The following summarizes the recommended topics for R&D on asset monitoring for the next two decades:

- Develop embedded sensing
- Co-design, and seamlessly integrate into manufacturing, the sensing method and the asset structure
- Develop sensors considering the system-level aspects of design and interfaces for autonomous initiation, data processing, self-calibration, and energy management for self-sustained operation on
- Develop next-generation multi-functional sensor platforms
- Focus on wireless protocols that align with the goals of smart grid technology
- Develop DLR technology with forecasting capability over a wide range of time frames
- Develop methods for seamlessly and easily integrating DLR products into the transmission system
- Devise a top-down approach to drive DLR commercialization by identifying high-value DLR application(s) in control rooms, in close collaboration with utilities and industry
- Investigate the potential for AI to enable DLR with high-accuracy forecasting capability from hour to daily time frames (including addressing the complexity of weather change and control room response plans when DLR rating prediction is overestimated)

2.3.3 Advanced Timing

Timing technologies are essential in transmission system measurements. Different timing technologies have been studied and applied. We focus here mainly on timing distribution in large geographic areas (nationwide) rather than individual distribution networks.

2.3.3.1 Current Situation, Challenges, and Barriers

GPS is the most popular timing technology, widely installed and used in synchronized measurements. With a typical timing accuracy of 100 nanoseconds, GPS signals can provide perfect synchronization to power system devices. However, remote locations, such as transmission substations, might not be appropriate for receiving GPS signals. There will likely be multiple timing technology choices for transmission system measurement in the near future. Two existing time-synchronization technologies, Network Time Protocol and Precision Time Protocol, can transmit accurate, synchronized timing signals from the timing signal generation subsystem to remote locations without the installation of a synchronization timing source at each location. In addition to Network Time Protocol and Precision Time Protocol, local atomic clocks, such as Cs clocks, can provide precise timing signals to remote locations. However, the cost and aging factor of atomic clocks make them an uncertain option for transmission system measurement. Other advanced technologies are also being studied, such as timing sources from pulsars.

2.3.3.2 Technology and R&D Recommendations for Advanced Timing

In addition to developing new timing sources, technologies that improve the quality of existing timing sources, such as timing signal shift detection and alignment and timing signal spoofing and protection, are critical to having accurate future timing technologies for the grid. With the development of these technologies, existing timing sources can be more precise and safer to use for transmission system measurements.

We identify four RD&D areas in which DOE support could advance timing technology for power systems: (1) precise timing sources from the universe, (2) hybrid source-based timing technology, (3) time shift detection and alignment, and (4) timing system spoof detection and protection.

Precise timing sources from the universe

In addition to the timing signals that can be obtained from GPS or crystal oscillators, indestructible and precise timing signals come from the universe. Pulsars, which are essentially compact, highly magnetized rotating neutron stars, are very good examples. The rotation periods of most pulsars are between 1 millisecond and 1 second with a deviation of less than 10^{-15} second per second (even less than 10^{-18} second per second for some pulsars). Additionally, pulsars have long-term stability that extends to millions of years, much longer than terrestrial atomic clocks. More importantly, using pulsars offers higher security than using existing time sources because it would be impossible to attack pulsars in the anticipated future. In astrophysics, the pulsar timing array was specifically designed to detect and analyze gravitational waves. Motivated by this vital application of pulsars in astronomy, researchers have recently recognized potential applications of pulsar-based precise timing in electric power grids. Because precise timing is the prerequisite of accurate, synchronized power grid measurements, there

would be tremendous technical and economic benefits if pulsar-based precise timing could be used in power systems to enable coordinated wide-area monitoring and controls.

However, no pulsar-based timing instrument is available on the market, and one cannot be assembled from market-available parts. Designing a pulsar-based timing instrument and developing pulsar-based timing applications for electric power grids require R&D by power system researchers.

Hybrid-timing-source-based technology

Conventional transmission system measurements rely mainly on references such as GPS signals for time synchronization. However, various uncontrollable, unpredictable factors (e.g., atmospheric disturbances, weather changes, GPS signal attacks, and solar activity) can cause GPS receivers to lose signal occasionally even if their antennas have an unobstructed view of satellites. When GPS signals are defective, transmission system measurement devices can generate significant errors. Erroneous PMU voltage or current measurements resulting from GPS anomalies could lead to a chain of mis-operations in power system control and protection.

To address this issue, a reliable back-up timing source, such as a pulsar signal, could be integrated with the GPS synchronization system to create a hybrid-timing-source-based system. When the performance of the GPS timing signal is unsatisfactory, hybrid timing sources can be coordinated to give a more precise, reliable synchronization.

Additionally, chip-scale atomic clock (CSAC) and enhanced long-range navigation (eLoran) approaches could be used as timing alternatives in future grid monitoring. CSAC has been tested for PMUs and can, overall, provide very accurate timing in the short term, with slow drifts in timing error (about 1 microsecond in 24 hours). Because of the slow timing drift, CSAC could be a reliable timing back-up for wide-area grid synchronization when GPS timing is unavailable or threatened. The main challenge is CSAC's high cost, which should decrease in the future as the distribution system market grows and manufacturing advances. Another promising timing alternative in the future is the eLoran timing technology. This high-power, low-frequency, ground-wave-based system can provide coordinated universal time (UTC) timing in wide areas, wholly independent of the Global Navigation Satellite System. Its UTC timing traceability is less than 50 nanoseconds, sufficient for grid measurement synchronization. The eLoran timing capability was tested for the first time in wide-area grid monitoring; the test demonstrated that eLoran can provide GPS-level timing accuracy and higher timing availability [83]. CSAC is a local timing source, and eLoran transmits timing in high-power signals, so these two options have offer high cybersecurity compared with GPS timing, which would contribute to greater timing security in the future grid.

Time shift detection and alignment

Monitoring system timing accuracy is normally in the 100-nanosecond range with good GPS reception. However, several uncontrollable, unpredictable factors, such as temporal hardware malfunction or unstable GPS signal, can cause imperfect synchronization and skew the time of corresponding on-site transmission system measurements even after calibration. Time shift in synchrophasor data will adversely influence the performance of applications that have stringent synchronization requirements,

such as power system protection, fault location, oscillation detection, and event triangulation. Even worse, in real situations, time shift in transmission system measurements is tiny, usually less than 1 second, making it difficult to detect because the time-shifted synchrophasor data still appear to be correct. As an increasing number of transmission system measurements are deployed in power grids, the need to detect synchronization issues and monitor the status of on-site transmission system measurements increases.

Timing system spoof detection and protection

Transmission system measurements rely on sources such as GPS to obtain global timing for synchronization. However, timing signals such as GPS civilian signals are unencrypted, and their power is as low as -160 decibel watts, which makes them vulnerable to external spoofing attacks. Therefore, system spoof detection and protection are important for transmission system measurements. By studying the behavior of timing system spoofing and the characteristics of timing sources, we can learn to detect timing system spoofs and devise means to protect transmission system measurements from attack.

The list below summarizes the recommended advanced timing R&D activities for the next two decades:

- Develop a pulsar-based timing instrument and pulsar-based timing applications for the electric power grid
- Develop hybrid timing system(s) that can be coordinated to give precise, reliable time synchronization when GPS timing signals are unsatisfactory
- Develop time shift detection and alignment
- Develop timing system spoof detection and protection to mitigate the spoofing vulnerability in GPS and other timing sources

2.3.4 Role of DOE

Table 10 summarizes the areas where DOE is well suited to support the recommended R&D efforts for advanced sensors and to address barriers.

Table 10. DOE’s Role in Supporting the Recommended Advanced Sensors R&D and Addressing Barriers

R&D Technology Area	Recommended Role of DOE
Synchronized measurements	<ul style="list-style-type: none">• Support deployment of timing technologies, including long-term performance demonstration, system-level integration of multiple time sources, and benefit-cost analysis• Promote collaborative efforts among research organizations, industry, and utilities to define and quantify the requirements for synchronized measurements, to guide R&D of synchronized measurement technologies• Assist in development of strategy for easy data-sharing among different organizations to enable development of measurement intelligence and other artificial intelligence applications in power systems
Optical monitoring systems	<ul style="list-style-type: none">• Facilitate collaborative efforts among national laboratories, industry to promote adoption of optical potential/current transformers in power systems

R&D Technology Area	Recommended Role of DOE
Asset monitoring systems	<ul style="list-style-type: none"> Working with utilities and national laboratories, facilitate industry partnership to identify high-value applications of DLR in power system operation and promote adoption and commercialization of DLR
Advanced timing	<ul style="list-style-type: none"> Promote collaboration among R&D organizations, industry, and utilities to determine the market potential for, and barriers to, new timing technologies

2.3.5 R&D Recommendations Summary

Advanced sensors and sensor systems provide utilities, balancing authorities, and other stakeholders with the information needed to make operational decisions that support system reliability and resilience as well as long-term planning. The changing generation mix and increasing bidirectional flow of power on the grid along with an increasing number of grid services necessitate more frequent collection and analysis of measurements and data from a larger set of sources than has been required in the past. As the frequency of measurements increases advanced sensors and asset monitoring will also need to be connected to highly accurate, reliable, available communication systems to transmit accurate, timely data and to correlate data from various sources, in order to support decision making. Table 11 summarizes advanced sensor R&D recommendations to improve grid resilience and reliability for the next 20 years.

Table 11. Advanced Sensors R&D Recommendations Summary

R&D Technology Area	Recommended R&D	R&D timeline
High-fidelity sensors	<ul style="list-style-type: none"> Synchronized measurements <ul style="list-style-type: none"> Develop alternative/GPS-independent timing technologies to enhance data quality Develop application-driven synchronized measurement technologies so that overall monitoring system performance meets the needs of power system applications Develop measurement intelligence, including measurement algorithms intelligence and distributed measurement intelligence to enhance measurement accuracy, reliability, availability, security, and versatility Combine multiple measurement functions in one device, including synchronized measurements, point-on-wave measurements, power-quality measurements, transients, and dynamics recording Research use of extremely low-computational-cost measurement methods allowing ubiquitous synchronized measurements in various grid equipment Optical monitoring systems <ul style="list-style-type: none"> Develop optical sensor characterization platform to comprehensively evaluate the performance of optical devices under various grid operation conditions; compare performance of optical sensors to performance of traditional PTs/CTs to justify optical sensors' advantages Conduct field demonstrations and long-term testing of optical devices in collaboration with utilities, e.g., by installing optical sensors at substation integrated with devices such as relays, power quality analyzers and PMUs Address the data interface between optical sensor devices and legacy grid devices 	<ul style="list-style-type: none"> Synchronized Measurements: Near term (5-10 years), critical to overcome the challenges that prevent applications of synchronized measurements in control rooms for real-time grid control and protection Optical monitoring systems: Near term (5-10 years) to take advantage of optical monitoring systems many advantages over PT/CTs and potential to improve grid measurement

R&D Technology Area	Recommended R&D	R&D timeline
	<ul style="list-style-type: none"> ○ Reduce the cost of optical devices so they can compete with traditional devices ○ Conduct pilot projects to demonstrate the advantages of optical devices over traditional devices, e.g., using a multiple-parameters grid monitoring system with optical devices to address high-impact real-world problems that industry and utility face, such as wildfire detection and mitigation, and LPT partial discharge detection and location 	resolution, safety, and reliability, as well monitor multiple parameters
Asset monitoring	<ul style="list-style-type: none"> • Develop embedded sensing for asset monitoring, e.g., co-design and seamless integration of sensing method and asset structure. • When developing sensors, consider system-level design and interfaces for autonomous initiation, data processing, self-calibration, and energy management for self-sustained operation • Develop next-generation multi-functional sensor platforms • Focus on wireless protocols that align with the goals of smart grid technology • Collaborate with utilities and industry to identify high-value DLR application(s) in the control room and to develop DLR technology that has prediction capability over a wide range of time frames and that is easy to integrate into existing transmission system • Develop or adopt methods to assess or manage the potential risks associated with new tools and methods, or propose methods used for qualification of new technologies • Research AI for to enabling DLR with high accuracy forecasting capability from hourly to daily time frame; promote development of control room response plans to address circumstances when the DLR rating prediction is overestimated 	<ul style="list-style-type: none"> • Near term (1-5 years) to help improve penetration of asset monitoring in energy systems
Advanced timing	<ul style="list-style-type: none"> • Develop a pulsar-based timing instrument and pulsar-based timing applications for the electric power grid • Develop hybrid timing system(s) so that, when the performance of GPS timing signals is unsatisfactory, hybrid timing sources can be coordinated to give more precise, reliable synchronization • Develop time shift detection and alignment • Develop timing system spoof detection and protection to mitigate the spoofing vulnerability in GPS and other timing sources 	<ul style="list-style-type: none"> • Near term (1-5 years). because timing is the fundamental component for synchronizing grid monitoring and timing accuracy determines the quality of data synchronization

DOE = U.S. Department of Energy; R&D = research and development; GPS = global positioning system; PT = potential transformer; PMU = phasor measurement unit; LPT = large power transformer; CT = current transformer; DLR = dynamic line rating; AI = artificial intelligence

2.4 Advanced Protection Systems

As power delivery systems evolve, so must the devices, methods, and schemes that protect those systems. Fundamental characteristics that have defined the power grid and associated protection schemes for the past century no longer hold in many cases, and operational expectations are increasing. DER such as solar photovoltaics and wind generation are being introduced to the system at an increasing rate. At the same time, technological advances such as incorporation of modern communication architecture, development of advanced sensors, and the trend toward system-wide interoperability provide many opportunities to modernize protection schemes to handle today's added complexity.

The relay protection system of the future will need to be:

- Flexible enough to handle complex topologies and operational requirements
- Able to incorporate communication while being robust against cyber-physical threats
- Less dependent on fault current magnitude
- Sensitive enough to detect faults and reliable enough to avoid mis-operations

DOE and Oak Ridge National Laboratory, with input from more than 70 utility partners, academics, and national laboratory participants, produced a document in 2019 entitled “Roadmap of Protective Relaying for the Future.” that document contains a plan for ensuring that transmission and distribution system protection schemes will be designed, installed, operated, and maintained to accommodate all new technologies affecting the electricity grid in both the near and distant future. Much of the material below is based on that plan.

2.4.1 Current Situation, Challenges, and Barriers

Several current and emerging challenges require new system protection technologies and philosophies.

Increased penetration of inverter-based generation: Because of the increasing feasibility of renewables and storage, inverter-based power generation (e.g., wind and solar) is increasingly common in both the bulk and distributed power systems. The shift away from rotating synchronous machines comes with many benefits but also faces many challenges. With regard to protecting the power system, the most impactful challenge associated with the move to inverter-based generation is the relatively low fault current contributed by inverter-based generators. Faulted, synchronous generators produce very large fault currents, often 500–1,000% of the rated load current; this allows for a wide range of discrimination between “normal” and “faulted” conditions. This wide range not only enables reliable detection of faults but also enables overcurrent protection schemes to filter out “transitory” events such as motor starting and inrush current; this tactic limits false tripping and increases selectivity. Furthermore, the intrinsic ride-through capability of synchronous generators promotes system stability by supporting voltage and compensating for the amount of generation lost immediately in a particular event. This characteristic of synchronous machines gives time for the appropriate protection response to isolate the fault.

In contrast, inverter-based generation does not intrinsically provide an inertial response, nor does it contribute significantly higher current under faulted conditions. Fault current for inverter-based generation is generally less than twice the load current and can be as low as 100–110% of the load current. While modern inverter-based generation has ride-through capability, legacy generation—particularly distributed generation—does not and will trip under most abnormal grid conditions. Because the difference between load current and fault current is so significant for synchronous machines, faults can be reliably detected using current-based protection schemes such as overcurrent and impedance relays. Because inverter-based generation does not exhibit this same characteristic

difference between load and fault current, current-based schemes will become less reliable as inverter-based generation displaces conventional synchronous generation.

Furthermore, because of the nature of inverter-based generation, protection schemes must be flexible enough to handle a wide variety of generation mixes. Traditionally, available fault current has been considered relatively stable for protection studies. Using solar power as an example, the generation mix will often shift from synchronous to inverter-based generation sources as solar comes online during the day. As this transition takes place, the available fault current and system behavior in a given portion of the system can vary significantly. For the emerging grid, determining the potential mix of sources will be a significant challenge, and the complexity of protection studies will increase significantly.

Increasing topological complexity (including microgrids): Multi-terminal lines—lines that have more than just a sending and a receiving end—present many challenges for protective relaying, including speed, reliability, and security. Many scenarios need to be considered and compared with a traditional two-terminal configuration. Factors that impact the effectiveness of the protection scheme for multi-terminal lines include line topology, tap-point locations, and the strength of the sources of infeed (i.e., current feeding into the zone) and outfeed (i.e., current flowing out of the zone).

Communications-assisted current differential schemes often provide the best solution for multi-terminal lines. Although these differential relay schemes offer some security, they can be affected by system conditions during internal line faults, which makes it difficult to set the relay to operate appropriately for all line faults under all expected operating conditions.

At the distribution level, modernization efforts involving DER, automated reconfiguration, and microgrids present many challenges for protective relaying. Much like what happens in transmission systems, complexities are created by dynamic topology and load tap-point locations. Unlike a transmission system, which traditionally has a networked configuration, the vast majority of the distribution system is radial, meaning each circuit has a single source, and all loads are fed from this source. For this reason, distribution systems are primarily protected with non-directional overcurrent, and coordination is achieved assuming that fault current reduces as distance from the substation increases. To protect reliability, automatic reclosers detect overcurrent conditions, interrupt momentary faults, and then auto-reclose in an attempt to restore service caused by these temporary faults while avoiding interruptions to the upstream primary feeder source. Many fuses are used as circuit protectors for back-up of primary overcurrent devices, and lateral and transformer fuses are used to isolate permanently faulted circuit-tapped load and distribution transformers. As distributed sources are added to this system and the path to the substation becomes less static, these design assumptions become less valid, and new methods for distribution protection are needed. Bidirectional and often variable power flow and variable short-circuit contributions can severely impact a system's ability to maintain reliability because of issues with protection coordination, speed, security, and selectivity. These issues are further compounded by sparse switchgear, protective relaying, and communications infrastructure on the distribution system.

Increased dependency on communication: In the recent past and even today, communication reliability and security were achieved using direct-wired communication. However, direct wiring generally requires huge investments in infrastructure. Some electric utilities may opt for dedicated communication networks for their protection systems while others may use communication systems managed and used by other utility systems and users. In either case, more communications in protection system devices means more vulnerability to cyber and cyber-physical attacks.

Many protection schemes today rely on communication (e.g., pilot schemes, blocking schemes, transfer trip, group setting changes); this dependency will increase in the future as relays are required to maintain a reliable protection scheme under much more dynamic system conditions.

Proliferation of DER: Many new types of DER have emerged during the past decade, resulting in complex challenges for grid integration. DER are small power sources typically connected at the distribution or customer level. Common types of DER include photovoltaics, batteries, diesel generators, and combined heat and power systems; they may also include fossil-fuel steam turbines, combustion turbines, microturbines, hydro turbines, geothermal engines, reciprocating engines, wind turbines, flywheels, small modular reactors, fuel cells, landfill gas, and controllable loads. These sources depart from the traditional one-way model in which the utility generates electricity and serves customer loads, and they complicate distribution system protection design by breaking the radial distribution paradigm.

DER can add great complexity to the design of protective relaying, considering factors such as topology, interconnection points, intentional islanding schemes, electronic interfaces, operation modes, resource availability, generation size, and fault current characteristics. DER and distributed loads create many taps and infeeds, which reduces the applicability of the differential relaying schemes found on transmission systems. Reliability, speed, dependability, and security can be compromised because of the potentially large number of operating constraints, configurations, and low-magnitude or variable short-circuit current contributions.

Non-electrical sensors: Traditionally, power system protection is based only on measurement of electrical characteristics (i.e., voltage and current), but sensors that measure other non-electrical characteristics, such as pressure rise; thermal departures; and acoustic, vibration, and atmospheric conditions, are becoming more common. Protective schemes may be able to use these sensors, as well as technologies such as industrial optical vision systems, to supplement and enhance the security of electrical measurements. As DER penetration increases, the need for high-fidelity, cost-effective sensors will also increase. Although potential exists for these sensors to supplement traditional electrical sensors in many protection system functions, incorporating these sensors can also open protective devices to cyber-physical attacks.

Software and models: Commercial power system short-circuit software is specifically designed for use in system engineering design, protective relay-setting study calculations, and protective relay coordination. These software modeling packages typically calculate the maximum available fault current using sub-transient impedances. Many allow engineers to rapidly model and use dynamic

relaying curves to assess and adjust protection coordination accordingly. Many of these modeling tools consist of a raw text file; some have highly developed databases that can be used to store protective relay settings. Although these tools are good for studying conventional power systems, they often lack the ability to account for inverter and hybrid machine–inverter–based dynamic fault current characteristics. These types of sources can significantly affect the overall performance, sensitivity, and selectivity of conventional protection schemes and therefore must be considered when the system is dominated by them.

Reduced fault current availability: Increasing inverter-based generation will reduce the magnitude of the current during faults. Traditional protective relaying schemes and system stability are historically highly dependent on high-magnitude fault current contributions for proper discrimination between normal operation and abnormal short-circuit events. The reduced availability of fault current resulting from the integration of distributed generation can severely limit a protection scheme’s ability to be fast, dependable, and selective over the wide range of fault conditions while not mis-operating or falsely tripping for normal power-system operations. Although lower levels of available short-circuit current may prevent arc flash and reduce interrupting rating capabilities, the need for advanced adaptive protection schemes increases for these more tightly controlled systems. These systems result in greater issues with power quality (e.g., transient and temporary overvoltage, harmonics), which can create complex issues related to protective relaying operation and therefore require more sophisticated signal processing, filtering, restraints, and speed.

Cyber-physical security: As communication and software become increasingly common in protection systems, the exposure to cyber-physical attacks grows. A cyber-physical system refers to a system such as the power grid that interacts and operates using both physical and computational elements. Modern protection systems must be robust against cyber and physical manipulation.

Cyber-physical attacks on modern protective devices can be undertaken by various means. Traditional cyber-security practices used in information technology systems may be insufficient to prevent cyber-security incidents involving power grid technologies because of differing hardware and system availability and responsiveness requirements. Therefore, research related to cyber-security technologies and electric power grid best practices has been ongoing. Furthermore, recent attacks on electric power grid devices and other SCADA technologies have demonstrated that such events are not only possible but feasible, and likely to occur more frequently in the future.

Cyber-physical attacks on protective devices have three main targets: software, hardware, and networks. These areas are defined below.

Software: Software attacks may target device firmware, device drivers, and software used to control and interact with protective devices (e.g., embedded web servers).

Firmware attacks generally replace vendor-provided firmware with firmware that contains malicious code. Because firmware updates from vendors are often provided over non-secure channels, attackers can intercept requests for firmware updates and provide a malicious version that the unsuspecting user loads onto the hardware. Additionally, because firmware is

often loosely controlled, attackers may reverse-engineer firmware to determine potential vulnerabilities.

Vendors often provide tools or lightweight web servers for convenient access to devices. Compared with other commercial software, these tools have much smaller development and support teams to discover and patch potential vulnerabilities. Furthermore, these configuration interfaces can be left with default values that are publicly known, making it easy for automated scanning tools to discover vulnerable systems and gain access to those systems.

Hardware: Hardware attacks may target relay hardware or sensors providing intelligence to the relay. They generally require physical access to the system to gain access to devices, which inherently limits the risk of these types of attacks. However, attacks that affect sensors (e.g., an attack on GPS) may not require physical access to a device.

Networks: Network attacks may target vulnerabilities in firewalls or take advantage of insecure protocols. Communication to relays needs to be secure, but the time-sensitive nature of protection limits the technologies and methodologies that are feasible to use to secure the networks.

Electromagnetic pulse/geomagnetic disturbance considerations: In the short term (5–10 years), it is reasonable to assume that industry advances in control/communication systems will progress faster (as is happening currently) than regulatory and standardization efforts to provide increased protection against electromagnetic pulse events.

The development of a consistent and effective electromagnetic pulse protection standard with which industry is required to comply should involve a systematic risk assessment with analysis of possible electromagnetic pulse threats and their consequences and recommended mitigation options. This would include impacts to both protection and redundancies.

To devise a defensible, effective, and economically viable set of protection guidelines, it is necessary to rely on extensive experimental test results. Future innovations in relay equipment designs can then be tested consistently. Furthermore, the analysis of threats and consequences must consider the effect of electromagnetic pulse events on communications systems because of the present trend toward increased reliance on remote control of devices in sparsely populated, distant locations.

Analytical and numerical methods in protection: Analytical approaches used to simulate the behavior of current power systems are deeply linked to the behavior of synchronous machines. For example, grid frequency is currently controlled mainly by synchronous generators. With increased use of inverter-based generation, classical approaches to power-flow analysis, voltage stability assessment, transient stability, protection coordination, and short-circuit calculations will not be fully valid. Therefore, new analytic approaches will need to be developed.

One of the main computational challenges of relays is accurately analyzing less-than-perfect voltage and current data quickly enough to meet the speed requirements of protection schemes. The advanced

functions in numerical relays require advanced filtering and signal processing to operate. The type of filtering and signal processing needed is determined based on the principal protection functions and application. For instance, overcurrent and distance relaying preserve fundamental frequency components and will reject all others to guarantee that these functions can properly coordinate with other similar relays on the system.

In general, most relay protection functions consider the content at power system frequency to be information, and everything else is interference or noise. Exceptions exist, such as harmonic restraints and voltage elements that use peak amplitude to detect non-power-frequency-related events. Additionally, some protection functions ignore fundamental frequency data so that specific components of interest can be detected. Such functions use filtering to account for DC-offset, subsystem frequency transients encountered with series-compensated lines, harmonics produced by non-linear loads or transformers, and high-frequency oscillations resulting from reflections for longer transmission lines.

The relaying industry has developed a number of methods to meet these computational requirements. For example, negative- and zero-sequence quantities can be used for overcurrent protection because they have small load current components compared with positive-sequence quantities, making the detection of a fault, fault type, and direction easier. However, the nature of the digital implementation of these algorithms can lead to false operation under certain conditions, particularly regarding polarizing quantities. Further research is needed to determine a robust algorithm using state-of-the-art computational methods and devices to meet the evolving speed and reliability needs of protection systems.

Distributed power-flow devices: Distributed power-flow devices are an emerging technology that is intended to allow more granularity of power flow on transmission systems. A number of these technologies are being developed and evaluated, but an existing method of distributed power-flow control has involved varying the impedance of transmission lines. This can affect protection and protection engineering in a number of ways. The devices themselves may drive a need for new adaptive protection schemes to compensate for this varying line impedance. Furthermore, developing planning and protection software requires models for the devices and the ability to dynamically vary line impedance.

Capacitive compensation for electromagnetic pulse events/geomagnetic disturbances: The power system must be hardened against phenomena such as geomagnetic disturbances, coronal mass ejections, and electromagnetic pulses. Several concept solutions for geomagnetic disturbances, coronal mass ejection, and electromagnetic pulse phenomena have been proposed, including more aggressive series compensation on transmission lines and switched-shunt compensation devices connected between transformer neutral and earth ground. Although these devices can block the induced DC currents generated by these phenomena, mitigation methods pose challenges for protective relaying security. Series-compensated lines have historically been used for very long power lines in the western United States. This type of power system typically requires very detailed protection analysis to ensure proper protective relay operation. Because of zero-sequence capacitive coupling paths, preventing mis-

operations due to faults on adjacent, mutually coupled lines is often challenging. Alternatively, switched neutral compensation devices could significantly impact the dependability of auto-transformer neutral-to-earth protection and advanced differential and associated restricted earth fault protection. More research is needed to assess whether the benefit of using this type of compensation outweighs the numerous challenges accompanying series-capacitive compensation.

Compatibility with legacy equipment: Modern protective relays are designed to use analog inputs from instrument transformers. Filters and signal processing are designed specifically for these technologies based on standards derived for legacy instrument transformers. This severely limits a utility's ability to test or adopt new advanced sensors such as optical current and voltage measurement devices. Because the analog interfaces are accepted as standard, relays can easily interface with legacy system components, but interaction with emerging sensors is often complicated. For example, a specific technology would need to convert its power measurements to connect through these analog inputs, and then these signals would be routed through the relay analog filtering and signal processing algorithms with a result no better than that of typical instrument transformers. This adds complexity (and cost) to the new technology and limits the ability to make use of beneficial characteristics such as improved fidelity and linearity.

Simulation for series compensation and special grounding: Modeling and simulation of protective relaying impacts caused by series and switched-shunt neutral compensation devices have been investigated under the DOE Advanced Grid Modeling Research program. This integrated co-simulation tool combined a commercial computer-aided protection engineering simulation platform with the Alternative Transient Program / Electromagnetic Transients Program to reproduce impedance protection relay mis-operation on a series-compensated line due to an adjacent line fault [84]. This demonstration was successful for a small-scale power system model, including implementation of front-end protective relaying generalized signal processing and filtering circuitry for a combined transient simulation of the event. The results were promising and matched closely with data from the event. Research opportunities exist for expanding these commercial protection tools to assess impacts on protective relaying schemes as mitigation devices are developed for some of the phenomena associated with geomagnetic disturbances, coronal mass ejections, and electromagnetic pulses.

2.4.2 Technology and R&D Recommendations for Advanced Protection

To meet the objectives of the future grid, research on advanced protection schemes will need to continue and be expanded to include setting-less relaying and the involvement of sensor technologies in protective relaying. It is recommended that DOE focus on the technical areas below.

2.4.2.1 Model-Driven Adaptive Relaying

Adaptive protective relaying schemes are needed to address the wide range of short-circuit contributions related to distributed generation and alternative configurations of the grid. Incorporating an internal power system simulator within local relays allows for automatic calculation of protection settings and adjustment of coordination with both local and remote terminals. These protective relays can adaptively coordinate for multiple contingencies and configurations of the power system they are protecting. For example, a field-programmable, gate-array-based, model-driven adaptive protection

relay has been developed that can calculate settings in real time and coordinate protection with other relays on the system to provide increased reliability, security, speed, and selectivity. These relay schemes need more research, but preliminary results have shown promise to fill many gaps in future protective relaying schemes.

2.4.2.2 Artificial Intelligence/Machine Learning

Advanced ML algorithms could benefit protective relay coordination by auto-tuning models or learning expected load levels. The goal of this type of algorithm would be to characterize and provide accurate parameters by learning normal system behavior as well as system responses during system breaker operations, fault events, and normal operations. Over time, this type of auto-tune feature could provide a good indication of model accuracy and optimization for understanding mutual coupling and system impedance characteristics for engineering design, protection coordination, and operations and could allow for higher-level assessments of the power system than are possible currently. Coordination of operational models could assist in fine-tuning of models for a wide range of system conditions.

Position navigation and timing will be important on the future power system. These services will be used for advanced AI/ML adaptive relay systems. Values for precision, integrity, and level of synchronization are to be determined based on current DOE research efforts for these protective relay systems. A sufficient communication structure and mitigation plan are needed for times when communication services are lost. Incorporating mitigations using advanced AI/ML techniques for understanding system configuration when position navigation and timing series are not available will enable advanced adaptive protective relaying to provide resilience and mitigation during these times.

Existing capability gaps include the inability to adapt when timing signals are lost. Techniques are needed for using non-simultaneity signatures of power system switchgear to understand system changes during moments when timing signals are not available. To develop these techniques, continued, increased funding is needed for work on advanced adaptive protective relaying with AI/ML.

Two documents, “Future State of Protective Relaying” (peer-reviewed white paper, 2018) and “Roadmap of Protective Relaying for the Future” (2019), address many aspects of advanced adaptive relaying and their implications for the electric power grid.

2.4.2.3 Setting-less (Coordination-less) Relays

Today’s commercial relaying schemes have multiple protective functions, each requiring complex settings and coordination among the functions, with relays for neighboring protection zones. A modern numerical relay has an average of 12 protective functions, making coordination is quite complex. This complexity increases the possibility of human error and improper protection actions and often leads to inconsistencies. Protection based on dynamic state estimation, sometimes called “setting-less protection,” aims to avoid these complex settings and coordination tasks. This approach is considered “setting-less” because it uses only the operating limits of devices. (“Coordination-less” protection might be a more accurately descriptive term). The method has been tested in the laboratory and will be field-tested in a New York Power Authority substation.

A dynamic state-estimation scheme continuously monitors protection-zone measurements such as voltage, current, and tap settings. Measurement data are used in a dynamic state estimator for the protection zone. A chi-square test is performed to determine how well the measured data fit the dynamic model of the protection zone. When the fit is within measurement accuracy, the estimation provides a true operating condition of the protection zone. Discrepancies indicate an internal abnormality. The fundamental idea is to check the consistency between the protection zone dynamic model and terminal measurements. Any mismatch between the model and measurements indicates that something is wrong inside the protection zone and that protective action is needed.

2.4.2.4 Integration with Sensors (Traditional and Non-Traditional)

Traditionally, protection is based on information from sensors that monitor the local electrical characteristics of voltage and current. Adding sensors that monitor other types of data can improve the performance of protective relays; however, communication, cyber security, and software will need to be improved to allow additional measurements to be safely included in the protection scheme. Furthermore, non-conventional sensors, such as optical voltage and current sensors, have significantly different characteristics, which could complicate their integration with conventional CT and PT measurements.

Sensors that measure physical characteristics, such as acoustic, vibration, and thermal data, can increase the robustness and reliability of the overall protection system by both informing the protection functions and providing notification of intrusion or attempted manipulation. Research is needed on how these sensors can improve protective device functionality.

2.4.3 Role of DOE

DOE could play a significant role in promoting and advancing protection systems and components necessary to support the rapid changes that will take place in grid architecture and operations over the next 20 years. DOE roles should include:

- Promoting and coordinating government, research organization, industry, and utility collaboration on defining the needs and requirements for advanced protection systems
- Promoting and coordinating, across DOE, co-simulation and model integration to ensure that system dynamics are accounted for in model results
- Promoting and coordinating industry collaboration on backward compatibility of equipment and ensuring that newly developed equipment is backward compatible, perhaps in collaboration with research organizations to define compatibility requirements for the equipment.

2.4.4 R&D Recommendations Summary

Table 12 summarizes our advanced protection systems R&D recommendations.

Table 12. Advanced Protection Systems R&D Recommendations Summary

R&D Technology Area	Recommended R&D	R&D timeline
Model-driven adaptive relaying	<ul style="list-style-type: none"> Incorporate an internal power system simulator within local relays to automatically calculate protection settings and adjust coordination with both local and remote terminals and adaptively coordinate for multiple contingencies and configurations of the power system they are protecting 	<ul style="list-style-type: none"> Near term (1-5 years) to allow time for development, commercialization, and adoption.
AI/ML	<ul style="list-style-type: none"> Develop algorithm to auto-tune models or learn expected load levels in order to characterize and provide accurate parameters by learning normal system behavior as well as system response during system breaker operations, fault events, and normal operations Incorporate mitigation techniques for system configuration when position navigation and timing series are not available 	<ul style="list-style-type: none"> Near term (1-5 years) to allow time for development, commercialization, and adoption.
Setting-less (coordination-less) relays	<ul style="list-style-type: none"> Develop protection based on dynamic state estimation (“setting-less protection”) which aims to avoid complex settings and coordination tasks and thereby reduce errors, and continuously monitors protection zone measurements, with mismatches between measured data and the dynamic model indicating that something is wrong inside the protection zone 	<ul style="list-style-type: none"> Mid term (10-15 years) to allow time for development, commercialization, and adoption.
Integration with sensors (traditional and non-traditional)	<ul style="list-style-type: none"> Develop sensors that measure physical quantities other than voltage and current, such as acoustic, vibration, and thermal sensors 	<ul style="list-style-type: none"> Mid term (10-15 years) to allow time for development, commercialization, and adoption.

Note: to accommodate ongoing and impending grid changes, these recommendations will need to be implemented during a 5- to 10-year time frame, so R&D work needs to begin as soon as possible.

3. Conclusions and Summary of Recommendations

Throughout most of the U.S. power grid's 100+ year history, the architecture, services, and required technologies have remained relatively consistent, allowing for evolutionary and incremental change to provide reliable service to meet demand. During the past 20 years, multiple significant changes have occurred, including: increased electrification; increases in distributed generation and proliferation of variable renewable energy; adaptations in how services are offered; increased need to keep the grid reliable and resilient; and the increased rate at which the grid must adapt. These changes make it challenging to define what the future grid will look like. In 2003, DOE developed a 20-year grid roadmap, and, in 2001, Massachusetts Institute of Technology studied the future of the electricity grid. Both documents evaluated the challenges and R&D required for the 2030 grid. Those two efforts arrived at similar conclusions about the challenges and R&D needs. In this white paper, we aimed to define the hardware challenges and R&D needed for the grid of 2040. The objective of this report is to identify technology gaps, challenges, and R&D opportunities for developing a reliable and resilient future grid in light of the abovementioned trends.

These challenges include:

- More variable renewable generation and DER
- Fast rate of system changes with slow grid infrastructure upgrades
- More frequent and extreme/abnormal weather events and physical attacks
- Greater reliance on information and communication technologies
- Greater environmental constraints and desire for sustainability

We performed a scenario analysis that looked at multiple future pathways for the grid to determine which technologies to highlight in this white paper. Technology solutions were identified to address the challenges outlined in each scenario. The technology solutions that rose to the top in the largest number of scenarios were selected for further evaluation.

Based on the results of this approach, we conclude that the following technology solutions will significantly shape the future of the U.S. electricity grid:

- **Power-flow control devices:** Transmission-scale reactive power devices, low-cost hybrid systems and energy storage, power electronic building blocks for multiple applications such as FACTS devices, solid-state transformers
- **High-power delivery over long distances:** Ultra-conductive systems, wireless power transfer, modular transformers, smart materials, or systems produced by advanced manufacturing
- **Advanced sensors:** High-fidelity sensors, asset monitoring (nondestructive evaluation, drone survey of lines), alternative timing and communications
- **Advanced protection systems:** Model-driven adaptive protection systems, negative sequence source and alignment to advanced sensor and communication technologies

Table 13 summarizes recommended roles for DOE to further the recommended R&D and assist in overcoming barriers. Table 14 summarizes the recommended technologies and R&D areas.

Table 13. Recommended DOE Role for Advancing Transmission Technology for the Future Grid

R&D Technology Area	Recommended DOE Role
Power System Electronics	
FACTS-based power-flow control devices	<ul style="list-style-type: none"> • Assist R&D for continuously improving reliability and cost performance of FACTS technologies • Promote industry coordination and collaboration to perform field demonstrations of advanced FACTS devices • Assist in the transition to full-scale demonstrations and comprehensive field applications of hybrid low-cost devices • Coordinate development of testbeds or testing facilities • Support development of comprehensive simulation tools/frameworks to facilitate modeling and analysis of FACTS technologies
Embedded HVDC systems	<ul style="list-style-type: none"> • Encourage and assist industry to expand field demonstration of embedded HVDC systems • Facilitate collaboration between industries and academic institutions to research MTDC application such as continent-level interconnection, renewable energy integration, and urban power grid uprating • Develop testbeds and test facilities for validating new technologies used in HVDC applications and identifying viable technology routes • Hold workshops for utilities, regulatory bodies, and government to introduce the latest progress on MTDC technology
Power electronic building blocks for multiple applications	<ul style="list-style-type: none"> • Support development of power stage subsystem common architectures that can be used across multiple applications, as well as designs that integrate multiple functions into one device
High Power Delivery Over Long Distances	
Electrical conductors	<ul style="list-style-type: none"> • Support near-term research and development through public-private partnerships to accelerate deployment of advanced conductor technologies • Support demonstration of advanced technologies to increase ampacity along existing corridors
Electrical insulators	<ul style="list-style-type: none"> • Support near-term research and development through public-private partnerships and encourage adoption through demonstration activities
Manufacturing processes	<ul style="list-style-type: none"> • Bring together industry, academia, and national laboratories to identify novel approaches using innovative processes, such as advanced manufacturing • Establish an advanced materials program focused on development of new materials and processes such as: <ul style="list-style-type: none"> ○ Soft magnetic materials adapted for advanced manufacturing ○ Structural composites with lightweight, high-strength, failure-proof materials to reduce weight and installation costs while enhancing reliability ○ Methods for cost-effective large-scale manufacturing of conductors and connectors ○ Cost-effective large-scale manufacturing of conductors and connectors using metallic matrix composite materials with improved electrical and mechanical properties ○ Processes for manufacturing carbon nanotubes and carbon nanotube-based conductors using low-cost abundant precursors, such as coal and natural gas, for fabricating connectors for a novel class of cables for electrical systems
Transformers	<ul style="list-style-type: none"> • Support advancement and acceleration of transformers, including modular transformers, through public-private partnerships • Support public-private partnerships to advance and accelerate testing and deployment of transformers, including modular transformers • Promote collaboration with DOE's Advanced Manufacturing Office with equipment manufacturers and utilities towards the development of modular transformers

R&D Technology Area	Recommended DOE Role
	<ul style="list-style-type: none"> Support development on new insulation materials, low-loss magnetic core materials, electrical conductors for windings, and cooling of transformers
Advanced Sensors	
Synchronized measurements	<ul style="list-style-type: none"> Support deployment of timing technologies, including long-term performance demonstration, system-level integration of multiple time sources, and benefit-cost analysis Promote collaborative efforts among research organizations, industry, and utilities in defining and quantifying the requirements for synchronized measurements to guide R&D of synchronized measurement technologies Assist in development of strategy for easily sharing data among different organizations to develop measurement intelligence and other artificial intelligence applications in power systems
Optical monitoring systems	<ul style="list-style-type: none"> Accelerate applications of optical PTs/CTs in power systems through collaborative efforts among national laboratories, industry, and DOE
Asset monitoring systems	<ul style="list-style-type: none"> Work closely with utilities to identify high-value applications of DLR in system operations, and work with utilities and national laboratories to support commercialization of DLR in U.S.
Advanced timing	<ul style="list-style-type: none"> Promote collaboration among R&D organizations, industry, and utilities to determine the market potential and barriers to new timing technologies
Advanced Protection Systems	
	<ul style="list-style-type: none"> Promote and coordinate government, research organization, industry, and utility collaboration on defining the needs and requirements for advanced protection systems Promote and coordinate, across DOE, co-simulation and model integration to ensure that system dynamics are accounted for in model results Promote and coordinate industry collaboration on backward compatibility of equipment and ensuring that newly developed equipment is backward compatible; collaborate with research entities and industry to define compatibility requirements for the equipment

DOE = U.S. Department of Energy; R&D= research and development; FACTS = flexible alternating current transmission system; HVDC = high-voltage direct current; MTDC = multi-terminal direct current ; PT = potential transformer; CT = current transformer; DLR = dynamic line rating

Table 14. R&D Recommendations

R&D Technology Area	Recommended R&D	R&D timeline
Power System Electronics		
FACTS-based power flow control devices	<ul style="list-style-type: none"> Accelerate the maturation of advanced FACTS-based devices and emerging low-cost devices, including promoting cost reduction and reliability improvement and field demonstrations and commercial applications of advanced FACTS-based devices, such as UPFC Develop capabilities for testing emerging power-flow control technologies in a lab environment that closely resembles field conditions (it is often impossible to test these devices in the real power grid, so such testbeds are needed to help these technologies evolve) Promote use of iron core-based FCLs and integrated use of FCLs with other power-flow control devices to help relieve fault conditions on the other power-flow control devices and relax design requirements, which, in turn, will improve reliability and lower overall costs for power-flow control applications 	<ul style="list-style-type: none"> Near term (1-5 years) because the R&D cycle of FACTS technologies is long, and emerging technologies need test facilities for validation studies
Embedded HVDC systems	<ul style="list-style-type: none"> Promote field demonstrations of multi-terminal VSC-HVDC systems 	<ul style="list-style-type: none"> Near term (1-5 years) because field

R&D Technology Area	Recommended R&D	R&D timeline
	<ul style="list-style-type: none"> • Develop hybrid DC circuit • Develop AC-to-DC conversion 	demonstrations and commercial applications of embedded HVDC will significantly help development and deployment, and U.S. applications lag behind other countries
Power electronic building blocks for multiple applications	<ul style="list-style-type: none"> • Power stage subsystem <ul style="list-style-type: none"> ○ Develop MMC-based VSCs ○ Support advances in fundamental materials (e.g., magnetics, dielectrics) and their manufacturing into components (e.g., transformers, capacitors) ○ Develop high-voltage (20+ kV) WBG semiconductor devices • Control and protection subsystem <ul style="list-style-type: none"> ○ Develop system protection for WBG semiconductor devices and higher-voltage (e.g., >1 kV) DC systems ○ Promote innovation in controllers, sensors, and auxiliary power supplies to support wider use of WBG semiconductor devices • Thermal management <ul style="list-style-type: none"> ○ Develop new materials, more compact mechanical components, tighter integration with passives and packaging, and understanding of broader system interactions ○ Develop methods of packaging of WBG semiconductor devices to accommodate their high-frequency, high-temperature, and high-voltage operation 	<ul style="list-style-type: none"> • Near term (1-5 years) to allow time for development, testing, integration
High Power Delivery Over Long Distances		
Electrical conductors	<ul style="list-style-type: none"> • Accelerate development of alloys with improved electrical and mechanical properties using integrated computational materials science & engineering approach • Modify surface of metallic conductors to improve their oxidation and corrosion resistance while preserving low interfacial electrical resistance between conductors and connectors • Optimize engineering of interfaces between matrix and carbon nanotubes to minimize electron scattering and losses in metallic matrix composites; optimize design of metallic matrix composites by determining the distribution of sizes of carbon nanotubes, their structure (e.g., single-wall vs. multi-wall), aspect ratio, concentration, and orientation to maximize structural and electrical properties. • Develop carbon-based conductors, with emphasis on obtaining meso-scale structures that exhibit the inherent physical and mechanical properties of nano-phased materials • Develop processes to manufacture connectors for integrating cables into electrical systems 	<ul style="list-style-type: none"> • Near term (1-5 years) based on EIA Annual Energy Outlook 2020 and number of miles of high-voltage transmission lines that will reach end of useful life in the next 10 to 20 years
Electrical insulators	<ul style="list-style-type: none"> • Support research to discover polymeric materials that exhibit high dielectric breakdown strength and environmental durability <ul style="list-style-type: none"> ○ Investigate the effect of adding nanoparticles of SiC, BaTiO₃, and ZnO to polymer matrix composites to reduce the impact caused by space charge ○ Determine the role of nanoparticle size distribution, concentration, and dispersion; the nature of the 	<ul style="list-style-type: none"> • Near term (1-5 years) based on the EIA Annual Energy Outlook 2020 and number of miles of high-voltage transmission lines that will reach end of useful life in the next 10 to 20 years

R&D Technology Area	Recommended R&D	R&D timeline
	<p>interface between a nanoparticle and polymeric matrix; and the resistance of the composite to moisture and temperature</p> <ul style="list-style-type: none"> • Perform multi-physics simulations to determine the response of HVDC cables to the simultaneous application of thermal and electromagnetic fields, structural loads, and environmental effects (e.g., wind, rain, snow), coupled with topology optimization techniques to identify geometrical features that could mitigate the effect of space charge accumulation 	
Manufacturing processes	<ul style="list-style-type: none"> • Research manufacture of grid components, such as motors and transformers, using metals and other materials • Develop soft magnetic materials adapted for advanced manufacturing • Develop structural composites using lightweight, high-strength, failure-proof structural materials to reduce weight and installation costs while enhancing reliability • Develop methods for cost-effective large-scale manufacturing of conductors and connectors • Develop cost-effective large-scale manufacturing of conductors and connectors using metallic matrix composite materials with improved electrical and mechanical properties • Develop processes for manufacturing carbon nanotubes and carbon nanotube-based conductors using low-cost abundant precursors, such as coal and natural gas, for fabricating connectors for a novel class of cables for electrical systems 	<ul style="list-style-type: none"> • Near term (1-5 years) to develop advanced materials and manufacturing methods that may be installed to accommodate the end of useful life of existing infrastructure
Transformers	<ul style="list-style-type: none"> • Modular transformers <ul style="list-style-type: none"> ○ Standardize modular transformer components so that transformers can be transported to any substation or utility without the need for redesign • Develop customizable component (possibly through specific power electronics) that allows for the transformer's performance characteristics to meet specific needs 	<ul style="list-style-type: none"> • Near term (1-5 years), focused on power electronics and need to deploy transformers quickly in response to an event
Advanced Sensors		
High-fidelity sensors	<ul style="list-style-type: none"> • Synchronized measurements <ul style="list-style-type: none"> ○ Develop GPS-independent/alternative timing technologies for synchronized measurements ○ Develop application-driven synchronized measurement technologies so that the overall monitoring system performance meets the needs of power system applications ○ Develop measurement intelligence, including measurement algorithms intelligence and distributed measurement intelligence to enhance measurement accuracy, reliability, availability, security, and versatility ○ Develop multiple measurement functions, including synchronized measurements, point-on-wave measurements, power-quality measurements, transients, and dynamics recording in one device ○ Develop extremely low-computational-cost measurement methods allowing ubiquitous synchronized measurements of various grid equipment • Optical monitoring systems <ul style="list-style-type: none"> ○ Develop an optical sensor characterization platform to comprehensively test performance of optical devices under various grid operating conditions and compare results with 	<ul style="list-style-type: none"> • Synchronized Measurements: Near term (1-5 years) because R&D investment is critical to overcome challenges that prevent applications of synchronized measurements in control rooms for real-time grid control and protection • Optical monitoring systems: Near term (1-5 years) because these systems have many advantages over PT/CTs and could improve grid measurement resolution, safety, reliability, and provide multiple parameters monitoring

R&D Technology Area	Recommended R&D	R&D timeline
	<p>those for traditional PTs/CTs to justify optical sensors' advantages</p> <ul style="list-style-type: none"> ○ Collaborate with utilities to perform field demonstration and long-term testing of optical devices, e.g., with device installed at substation and integrated with relays, power quality analyzers, and PMUs ○ Address data interface between optical sensor devices and legacy grid devices ○ Reduce the cost of optical devices so they can compete with traditional devices ● Support pilot projects to demonstrate the advantages of optical devices over traditional devices, e.g., a multiple-parameter grid monitoring system using optical devices to address high-impact real-world problems that industry and utility face, such as wildfire detection and mitigation and LPT partial discharge detection and location 	
Asset monitoring	<ul style="list-style-type: none"> ● Develop embedded sensing for asset monitoring, e.g., co-design and seamless integration of sensing method and asset structure into manufacturing. ● In developing sensors, consider system-level design aspects and interfaces for autonomous initiation, data processing, self-calibration, and energy management for self-sustained operation, supporting technology transfer to manufacturing by focusing on synergy between the system functionality and manufacturing techniques ● Develop next-generation multi-functional sensor platforms ● Focus on wireless protocols that align with the goals of smart grid technology ● Collaborating with utilities and industry, identify high-value DLR application(s) for control rooms and develop DLR technology, with prediction capability for a wide range of time frames, that can easily be integrated into the existing transmission system easily ● Develop or adopt methods to assess or manage potential risks associated with new tools and methods, or propose methods used for qualification of new technologies ● Explore AI to enable DLR with high-accuracy forecasting capability from the hourly to daily time frame, accounting for the complexity of weather change; support control rooms in developing plans to respond when DLR rating prediction is overestimated 	<ul style="list-style-type: none"> ● Near term (1-5 years) because embedded, seamless integration of asset monitoring with advanced manufacturing could help improve penetration of asset monitoring
Advanced timing	<ul style="list-style-type: none"> ● Develop a pulsar-based timing instrument and pulsar-based timing applications for the grid ● Develop hybrid timing system(s) that can be coordinated together to give a precise, reliable synchronization when GPS is unavailable or malfunctioning ● Develop time shift detection and alignment ● Develop timing system spoof detection and protection to mitigate the spoofing vulnerability in GPS and other timing sources 	<ul style="list-style-type: none"> ● Near term (1-5 years) because timing is the fundamental component for grid monitoring synchronization, and the safety, reliability, and accuracy of timing determine the quality of data synchronization
Advanced Protection Systems		
Model-driven adaptive relaying	<ul style="list-style-type: none"> ● Incorporate an internal power system simulator within local relays to automatically calculate protection settings, adjust coordination with both local and remote terminals, and 	<ul style="list-style-type: none"> ● Near term (1-5 years) to allow time for development, commercialization, and adoption

R&D Technology Area	Recommended R&D	R&D timeline
	adaptively coordinate for multiple contingencies and configurations of the power system they are protecting	
AI/ML	<ul style="list-style-type: none"> Develop algorithm for auto-tuning of models or learning expected load levels with the aim of characterizing and providing accurate parameters by learning normal system behavior as well as system response during system breaker operations, fault events, and normal operations Incorporate mitigation techniques for system configuration when position navigation and timing series are not available, to provide resilience and mitigation during these times 	<ul style="list-style-type: none"> Near term (1-5 years), to allow time for development, commercialization, and adoption
Setting-less (coordination-less) relay	<ul style="list-style-type: none"> Develop protection based on dynamic state estimation ("setting-less protection") 	<ul style="list-style-type: none"> Mid term (10-15 years), to allow time for development, commercialization, and adoption
Integration with sensors (traditional and non-traditional)	<ul style="list-style-type: none"> Develop sensors that measure physical characteristics other than voltage and current, such as acoustic, vibration, and thermal sensors 	<ul style="list-style-type: none"> Mid term (10-15 years), to allow time for development, commercialization, and adoption

DOE = U.S. Department of Energy; R&D = research and development; FACTS = flexible alternating current transmission system; UPFC = unified power-flow controller; FCL = fault current limiter; VSC = voltage source converter; HVDC = high-voltage direct current; DC = direct current; AC = alternating current; MMC = modular multi-level converter; kV = kilovolt; WBG = wide bandgap; SiC – silicon carbide; BaTiO₃ = barium titanate; ZnO = zinc oxide; EIA = Energy Information Administration; PT = potential transformer; CT = current transformer; PMU = phasor measurement unit; LPT = large power transformer; DLR = dynamic line rating; GPS = global positioning system

4. References

- [1] NERC, "NERC Glossary of Terms," NERC, Atlanta, 2020.
- [2] "Glossary of Terms Used in NERC Reliability Standards," North American Electric Reliability Corporation, 8 October 2020. [Online]. Available: https://www.nerc.com/files/glossary_of_terms.pdf.
- [3] National Academies of Sciences, Engineering and Medicine, "The Future of Electric Power in the United States," the National Academies Press, Washington, DC, 2021.
- [4] S. Schmidt, "Toward a more resilient and flexible power grid," Phys.org, 15 December 2015. [Online]. Available: <https://phys.org/news/2015-12-resilient-flexible-power-grid.html>.
- [5] P. F. Schewe and J. H. Press, The Grid : A Journey Through the Heart of Our Electrified World, National Academies Press, 2007.
- [6] M. Amin and J. Stringer, "The Electric Power Grid: Today and Tomorrow," MRS Bulletin, vol. 33, p. 399–407, 2008.
- [7] B. H. Chowdhury, "Power Quality," IEEE Potentials, vol. 20, no. 2, pp. 5-11, Jan 2001.
- [8] N. Hingorani, "Flexible AC Transmission Systems," IEEE Spectrum, vol. 30, no. 4, pp. 40 - 45, 1993.
- [9] N. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems, Wiley-IEEE Press, 1999.
- [10] A. Sode-Yome, N. Mithulananthan and K. Y. Lee, "Comprehensive comparison of FACTS devices for exclusive loadability enhancement," IEEJ Trans. On Electrical & Electronic Eng., vol. 8, pp. 7-18, 2013.
- [11] D. Povh and D. Retzmann, "Development of FACTS for Transmission Systems," in IERE Central America Forum, San Jose, Costa Rica, 2003.
- [12] "Estimating the Costs and Benefits of the Smart Grid," Electric Power Research Institute, 29 March 2011. [Online]. Available: <https://www.epri.com/research/products/1022519>.
- [13] K. Habur and D. O’Leary, "FACTS for Cost Effective and Reliable Transmission of Electrical Energy," [Online]. Available: <https://www.scribd.com/document/86050846/FACTS-for-Cost-Effective-and-Reliable-Transmission-of-Electrical-Energy>.
- [14] F. H. Gandoman, A. Ahmadi, A. M. Sharaf, P. Siano, J. Pou, B. Hredzak and V. G. Agelidis, "Review of FACTS technologies and applications for power quality in smart grids with renewable energy systems," Renewable and Sustainable Energy Reviews, vol. 82, p. 502–514, 2018.

- [15] R. Shah, J. Sanchez, R. Preece and M. Barnes, "Stability and control of mixed AC-DC systems with VSC-HVDC: A review," IET Generation Transmission & Distribution, vol. 12, no. 10, 2018.
- [16] J. Yu , G. G. Karady and L. Gu, "Applications of embedded HVDC in power system transmission," 2012 Power Engineering and Automation Conference, Wuhan, pp. 1-6, 2012.
- [17] A. Dimitrovski, Z. Li and B. Ozpineci, "Magnetic Amplifier–based power flow controller," IEEE Transactions on Power Delivery, vol. 30, no. 4, p. 1708 – 1714, August 2015.
- [18] A. Dimitrovski, Z. Li and B. Ozpineci, "Applications of saturable-core reactors (SCR) in power systems," in T&D Conference and Exposition, Chicago, 2014 IEEE PES.
- [19] D. Divan, W. Brumsickle, R. Schneider, B. Kranz,, R. Gascoigne, D. Bradshaw, M. Ingram and I. Grant, "A Distributed Static Series Compensator System for Realizing Active Power Flow Control on Existing Power Lines," IEEE Trans. Power Del., vol. 22, no. 1, pp. 642-649, Jan. 2007.
- [20] D. Divan and H. Johal, "Distributed FACTS - A New Concept for Realizing Grid Power Flow Control," IEEE Trans. Power Electronics, vol. 22, no. 6, p. 2253 – 2260, Nov. 2007.
- [21] K. M. Rogers, Power System Control with Distributed Flexible AC Transmission System Devices, M.S. thesis, University of Illinois at Urbana-Champaign, 2009.
- [22] W. Song, Design and Control of Distributed Power Flow Controller, Ph.D dissertation, North Carolina University, 2010, 2010.
- [23] Y. Xin, G. Weizhi , N. Xiaoye , Z. Cao, J. Zhang, B. Tian, H. Xi, Y. Wang, H. Hong, Y. Zhang, B. Hou and X. Yang, , "Development of Saturated Iron Core HTS Fault Current Limiters," IEEE Transactions on Applied Superconductivity, vol. 17, no. 2, pp. 1760 - 1763, 2007.
- [24] G. Chen, M. Hao, Z. Xu, A. Vaughn, J. Cao and H. Wang, "Review of high Voltage Direct Current Cables.," CSEE Journal of Power and Energy Systems, vol. 1, no. 2, pp. 9-21, 2015.
- [25] G. Mazzanti and M. Marzotto, Extruded Cables for High-Voltage Direct-Current Transmission: Advances in Research and Development, First Edition, Wiley-IEEE Press, 2013.
- [26] M. Jeroense, "HVDC, the Next Generation of Transmission: Highlights with Focus on Extruded Cable Systems," IEEE Transactions on Electrical and Electronic Engineering, vol. 5, no. 4, pp. 400-404, 2010.
- [27] D. McDowell and S. Kalidindi, "The Materials Innovation Ecosystem: A Key Enabler for the Materials Genome Initiative," MRD Bulletin, vol. 41, no. 4, p. 326, 2020.
- [28] J. Pan, M. Callavik, P. Lundberg and L. Zhang, "A Subtransmission Metropolitan Power Grid: Using High-Voltage dc for Enhancement and Modernization," IEEE Power and Energy Magazine, vol. 17, no. 3, pp. 94-102, 2019.

- [29] K. Li, M. McGuire, A. Lupini, L. Skolrood, F. List, B. Ozpineci, S. Ozcan and T. Aytug, "Copper–Carbon Nanotube Composites Enabled by Electrospinning for Advanced Conductors," *ACS Applied Nano Materials*, vol. 3, no. 7, pp. 6863-6877, 2020.
- [30] O. Hjortstam, P. Isberg, S. Soderholm and H. Dai, "Can we achieve ultra-low resistivity in carbon nanotube-based metal composites?," *Applied Physics A*, vol. 78, pp. 1175-1179, 2004.
- [31] A. Lekawa-Raus, J. Patmore, L. Kurzepa, J. Bulmer and K. Koziol, "Electrical Properties of Carbon Nanotube Based Fibers and Their Future Use in Electrical Wiring," *Advanced Functional Materials*, vol. 24, pp. 3661-3682, 2014.
- [32] M. Hotz and W. Utschick, "The Hybrid Transmission Grid Architecture: Benefits in Nodal Pricing," *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 1431-1442, 2018.
- [33] M. Hotz and W. Utschick, "A Hybrid Transmission Grid Architecture Enabling Efficient Optimal Power Flow," *IEEE Transactions on Power Systems*, vol. 31, no. 6, pp. 4504-4516, 2016.
- [34] New York Transco LLC, "E-1, Description of Proposed Transmission Line," New York Energy Solutions, [Online]. Available: <https://www.ny-es.com/new-page-5>.
- [35] A. Mannodi-Kanakki, A. Chandrasekaran, C. Kim, T. D. Huan, G. Pilania, V. Botu and R. Ramprasad, "Scoping the polymer genome: A roadmap for rational polymer dielectrics design and beyond," *Materials today*, vol. 21, no. 7, pp. 785-796, 2017.
- [36] D. Haught, J. Daley, P. Bakke and B. Marchionini, "Overview of the U.S. Department of Energy (DOE) High Temperature Superconductivity Program for Large Scale Applications," *International Journal of Applied Ceramic Technologies*, vol. 4, no. 3, pp. 197-202, 2007.
- [37] Y. Li, R. Cao, W. Huang, G. Li, Z. Guo and T. Liu, "Design and Simulation for the Control and Protection of Hybrid LCC-VSC MTDC System," in *IEEE 3rd International Electrical and Energy Conference (CIEEC)*, Beijing, 2019.
- [38] X. Xiang, M. M. C. Merlin and T. C. Green, "Cost analysis and comparison of HVAC, LFAC and HVDC for offshore wind power connection," in *12th IET International Conference on AC and DC Power Transmission (ACDC 2016)*, Beijing, 2016.
- [39] M. S. Jahan, S. J. Hamim, M. T. Imran Bhuiyan, M. J. Abeadin and M. N. Chowdhury, "Comparative cost analysis of VSC-HVDC and HVAC as transmission system for a 50 MW offshore wind farm in Hatiya Island," in *2nd International Conference on Sustainable Technologies for Industry 4.0 (STI)*, Dhaka, Bangladesh, 2020.
- [40] L. Barthold, R. Adapa, H. Clark and D. Woodford, "System advantages in conversion of AC transmission lines to DC," in *9th IET International Conference on AC and DC Power Transmission (ACDC 2010)*, London, 2010.

- [41] T. Meridji, F. Ceja-Gomez, J. Restrepo and R. Azar, "High-Voltage dc Conversion: Boosting Transmission Capacity in the Grid," *IEEE Power and Energy Magazine*, vol. 17, no. 3, pp. 22-31, 2019.
- [42] L. Reed, G. Morgan, P. Vaishnav and D. E. Armanios, "Converting existing transmission corridors to HVDC is an overlooked option for increasing transmission capacity," *Proceedings of the National Academy of Sciences*, vol. 116, no. 28, pp. 13879-13884, 2019.
- [43] A. Mokhberdoran, A. Carvalho, H. Leite and N. Silva, "A review on HVDC circuit breakers," in *rd Renewable Power Generation Conference*, Naples, 2014.
- [44] C. Du and C. Wang, "Review of DC Circuit Breaker Technology for HVDC Application," in *22nd International Conference on Electrical Machines and Systems (ICEMS)*, Harbin, China, 2019.
- [45] G. Adam, T. Vrana, R. Li, P. Li, G. Burt and S. Finney, "Review of technologies for DC grids – power conversion, flow control and protection," *ET Power Electron*, vol. 12, no. 8, pp. 1851-1867, 2019.
- [46] National Academy of Sciences; National Academy of Engineering; National Research Council; Committee on America's Energy Future, *America's energy future technology and transformation*, Washington, DC: National Academies Press, 2009.
- [47] *Enhancing the Resilience of the Nation's Electricity System*, National Academies of Sciences, Engineering, and Medicine, 2017, <https://doi.org/10.17226/24836>, 2017.
- [48] "Xcel Energy Information Sheet," 2021. [Online]. Available: <https://www.transmission.xcelenergy.com/>.
- [49] U.S. Department of Energy, "Quadrennial Technology Review: An Assessment of Energy Technology and Research Opportunities," U.S. Department of Energy, 2015.
- [50] M. H. Okba, . M. H. Saied, M. Z. Mostafa and T. M. Abdel- Moneim, "High voltage direct current transmission-A review, part I," in *IEEE Energytech*, Cleveland, OH, 2012.
- [51] "ASCE's 2017 Infrastructure Report Card," American Society of Civil Engineers, 2017. [Online]. Available: <https://www.infrastructurereportcard.org/americas-grades/>.
- [52] "Energy Flow Charts: Charting the Complex Relationships among," Lawrence Livermore National Laboratory, 2019. [Online]. Available: <https://flowcharts.llnl.gov/>.
- [53] "HVDC: When and How It Is Used in Transmission," Beta Engineering, December 2020. [Online]. Available: <http://www.betaengineering.com/BlogRetrieve.aspx?PostID=714193>.
- [54] "Ready for New HVDC Line, U.S. Lags Behind Rest of World," *Power Magazine*, 1 January 2017. [Online]. Available: <https://www.powermag.com/readying-new-hvdc-line-u-s-lags-behind-rest-world/>.

- [55] R. Davidson, "Ambitious Clean Line Energy 'wrapping up'," Windpower Monthly, 1 February 2019. [Online]. Available: <https://www.windpowermonthly.com/article/1523646/ambitious-clean-line-energy-wrapping-up>.
- [56] J. St. John, "7 Transmission Projects That Could Unlock a Renewable Energy Bounty," Green Tech Media, 9 April 2020. [Online]. Available: <https://www.greentechmedia.com/articles/read/9-transmission-projects-laying-the-paths-for-cross-country-clean-energy>.
- [57] J. Fialka, "U.S. Offshore Wind Needs to Clear a Key Hurdle: Connecting to the Grid," Scientific American,, 3 August 2020. [Online]. Available: <https://www.scientificamerican.com/article/u-s-offshore-wind-needs-to-clear-a-key-hurdle-connecting-to-the-grid/>.
- [58] "Annual Energy Outlook 2020," Energy Information Administration, Washington, DC, 2020.
- [59] C. Ourmansour, C. Underwood, G. Yurkevich and T. Bowie, "Modernising ageing transmission: A Golden Opportunity," Marsh & McLennan Companies, April 2020. [Online]. Available: <https://www.mmc.com/insights/publications/2020/apr/modernising-ageing-transmission.html>.
- [60] "Annual Energy Outlook 2020," Energy Informaiton Administration, Washington, D.C., 2020.
- [61] T. A. Short, Electric Power Distribution Handbook, CRC Press, 2003.
- [62] D. Bryant, "The Overlooked Benefits of High-Performance Powerline Conductors," Electricity Today, Power System Reliability Special Edition, vol. 33, no. 4, pp. 18-20, 2020.
- [63] X. Cui, Y. Wu, Z. Zhang, Y. Lui and X. Liu, "Study on the Improvement of Electrical Conductivity and Mechanical Properties of low Alloying Electrical Aluminimu Alloys," Composites Part B, pp. 381-387, 2017.
- [64] A. Bussmann-Holder and H. Keller, "High-Temperature Superconductors: Underlying Physics and Applications," Zeitschrift für Naturforschung B, vol. 75, no. 1-2, pp. 3-14, 2019.
- [65] E. Snider, N. Dasenbrock-Gammon, R. McBride, M. Debessai, H. Vindana, K. Vencatasamy, K. V. Lawler, A. Salamat and R. P. Dias, "Room-Temperature Superconductivity in a Carbonaceous Sulfur Hydride," Nature, vol. 586, no. 7829, pp. 373-377, 2020.
- [66] National Academies of Sciences, Engineering, and Medicine, "Frontiers of Materials Research: A Decadal Survey," National Academies Press, Washington, DC, 2019.
- [67] M. Wang, T. An, H. Ergun, Y. Lan, B. Andersen, M. Szechtman, W. Leterme, J. Beerten and D. Van Hertem, "Review and outlook of HVDC grids as backbone of the transmission system," CSEE Journal of Power and Energy Systems, pp. 1-12, 2020.
- [68] J. Gavin and S. Tapuch, "Microwave Wireless-Power Transmission to High-Altitude-Platform Systems," vol. 334, pp. 25-42, 2010.

- [69] P. E. Glaser, "Power from the Sun: It's Future," *Science*, vol. 162, no. 3856, pp. 857-861, 1968.
- [70] *Electric Power From Orbit: A Critique of a Satellite Power System*, Washington, DC: The National Academies Press, 1981.
- [71] National Research Council, "Solar Power Satellites," Washington, D.C., 1981.
- [72] H. Feingold, M. Stancati, A. Friedlander, M. Jacobs, D. Comstock, C. Shristensen, G. Maryniak, S. Rix and J. Mankins, "Space Solar Power: A Fresh look at the Feasibility of Generating Solar Power in Space for use on Earth," Science Applications International Corporation (SAIC), Chicago, Illinois, 1981.
- [73] "New ideas to increase the feasibility of space-based solar power and support the development of clean energy," ESA, 1 December 2021. [Online]. Available: <https://ideas.esa.int/servlet/hype/IMT?documentTableId=45087625530300097&userAction=Browse&templateName=&documentId=514a8db636ea637f6e27069183966350>.
- [74] C. T. Rodenbeck, P. I. Jaffe, B. H. Strassner II, P. E. Hausgen, J. O. McSpadden, H. Kazemi, N. Shinohara, B. B. Tierney, C. B. DePuma and A. P. Self, "Microwave and Millimeter Wave Power Beaming," *IEEE Journal of Microwaves*, vol. 1, no. 1, pp. 229-259, 2021.
- [75] E. Mazarico, X. Sun, J.-M. Torre, C. Courde, J. Chabé, M. Aimar, H. Mariey, N. Maurice, M. K. Barker, D. Mao, D. R. Cremons, S. Bouquillon, T. Carlucci, V. Viswanathan, F. G. Lemoine, A. Bourgoïn, P. Exertier, G. A. Neumann, M. T. Zuber and D. E. Smith, "First two-way laser ranging to a lunar orbiter: infrared observations from the Grasse station to LRO's retro-reflector array," *Earth, Planets and Space*, vol. 72, no. 1, pp. 1-14, 2020.
- [76] E. Cavallaro, "Researchers transmit energy with laser in 'historic' power-beaming demonstration," *Physics.org*, 28 October 2019. [Online]. Available: <https://phys.org/news/2019-10-transmit-energy-laser-historic-power-beaming.html>.
- [77] T. Rogoway, "How The Once Elusive Dream Of Laser Weapons Suddenly Became A Reality," *The Drive*, 25 November 2020. [Online]. Available: <https://www.thedrive.com/the-war-zone/37775/how-the-once-elusive-dream-of-laser-weapons-suddenly-became-a-reality>.
- [78] E. Ackerman, "Japan Demoes Wireless Power Transmission for Space-Based Solar Farms," 16 March 2015. [Online]. Available: <https://spectrum.ieee.org/energywise/green-tech/solar/japan-demoes-wireless-power-transmission-for-spacebased-solar-farms>.
- [79] D. Wagman, "Emrod Chases The Dream Of Utility-Scale Wireless Power Transmission," 26 August 2020. [Online]. Available: <https://spectrum.ieee.org/energywise/energy/the-smarter-grid/emrod-chases-the-dream-of-utilityscale-wireless-power-transmission>.
- [80] *Quadrennial Technology Review: An Assessment of Energy Technologies and Research Opportunities*, U.S. Department of Energy, 2015.

- [81] E. Taylor, C. Kramer, B. Marchionini, R. Sabouni, K. Cheung and D. F. Lee, "Materials Innovation for Next-Generation T&D Grid Components. Workshop Summary Report," 2015.
- [82] "Smart Grid Sensors Market Forecast to 2027 - COVID-19 Impact and Global Analysis by Sensor Type, Voltage Range, and Application," Research and Markets, September 2020. [Online]. Available: https://www.researchandmarkets.com/reports/5178590/smart-grid-sensors-market-forecast-to-2027?utm_source=BW&utm_medium=PressRelease&utm_code=r9q76v&utm_campaign=1458150+-+Smart+Grid+Sensors+Market+Forecast+to+2027+-+COVID-19+Impact+and+Global+Analysis+&ut.
- [83] S. Basker, J. Chop, R. Davis, T. Gunther, M. Herring, F. Hubert, D. Last, S. Lo, J. Merrill, K. Montgomery, M. Narins, C. Nichols, G. Offermans, B. Peterson, R. Wenzel and R. Wright, "Enhanced Loran (eLoran): Definition Document," International LORAN Association, 2007.
- [84] "DOE Advanced Grid Modeling Research Program," U.S. Department of Energy Office of Electricity, 2020. [Online]. Available: <https://www.energy.gov/oe/activities/technology-development/advanced-modeling-grid-research-program>.
- [85] "'GRID 2030" A National Vision for Electricity's Second 100 Years," U.S. Department of Energy: Office of Electric Transmission and Distribution, Washington, DC, 2003.
- [86] "National Electric Delivery Technology Roadmap," U.S. Department of Energy - Office of Electric Transmission and Distribution, Washington, DC, 2004.
- [87] "The Future of the Electric Grid," Massachusetts Institute of Technology, 2011.
- [88] "U.S. coal-fired electricity generation in 2019 falls to 42-year low," U.S. Energy Information Administration, 11 May 2020. [Online]. Available: <https://www.eia.gov/todayinenergy/detail.php?id=43675>.
- [89] Lazard.
- [90] "State Renewable Portfolio Standards and Goals," National Conference of State Legislature, 17 April 2020. [Online]. Available: <https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx>.
- [91] B. Storrow, "More coal has retired under Trump than in Obama's 2nd term," E&E News, 22 June 2020. [Online]. Available: <https://www.eenews.net/stories/1063430425>.
- [92] J. St. John, "2 More Western Utilities Move to Close Coal Plants Early, Shifting to Renewables and Storage," Green Tech Media, 29 June 2020. [Online]. Available: <https://www.greentechmedia.com/amp/article/two-more-western-utilities-move-to-close-coal-plants-early-shift-to-renewables-and-storage>.

- [93] P. Riley, "On the probability of occurrence of extreme space weather events," *Space Weather*, vol. 10, no. 2, 2012.
- [94] "Issues & Policy Electric Transportation," Edison Electric Institute, 2020. [Online]. Available: <https://www.eei.org/issuesandpolicy/electrictransportation/Pages/default.aspx>.
- [95] S. Madden, "Informing the Transmission Discussion," *Wires*, January 2020.
- [96] "Transmission Upgrades & Expansion: Keys to Meeting Large Customer Demand for Renewable Energy," David Gardiner and Associates, January 2018.
- [97] D. Roberts, "A national U.S. power grid would make electricity cheaper and cleaner," *VOX*, 20 June 2020. [Online]. Available: <https://www.vox.com/platform/amp/energy-and-environment/2020/6/20/21293952/renewable-energy-power-national-grid-transmission-microgrids>.
- [98] "TODAY IN ENERGY," U.S. Energy Information Administration, [Online]. Available: <https://www.eia.gov/todayinenergy/detail.php?id=36112>.
- [99] A. E. MacDonald, C. Clack, A. Alexander, A. Dunbar, J. Wilczak and Y. Xie, "Future cost-competitive electricity systems and their impact on U.S. CO₂ emissions," *Nature Climate Change*, 6, p. 526–531, 25 January 2016.
- [100] "Energy Analysis," National Renewable Energy Laboratory, 2020. [Online]. Available: <https://www.nrel.gov/analysis/seams.html>.
- [101] D. Roberts, "We've been talking about a national grid for years. It might be time to do it," 3 August 2018. [Online]. Available: <https://www.vox.com/energy-and-environment/2018/8/3/17638246/national-energy-grid-renewables-transmission>.
- [102] J. Temple, "China's giant transmission grid could be the key to cutting climate emissions," *Technology Review*, 2018.
- [103] "The world's longest power transmission lines," *Power Technology*, 27 July 2020. [Online]. Available: <https://www.power-technology.com/features/featurethe-worlds-longest-power-transmission-lines-4167964/>.
- [104] I. Penn, "It's Showtime for Elon Musk's Boring Co., With a Long Way to Go," *New York Times*, 8 December 2018.
- [105] EIA, "Assessing HVDC Transmission for Impacts of Non-Dispatchable Generation," U.S. Energy Information Administration, 17 June 2018. [Online]. Available: <https://www.eia.gov/analysis/studies/electricity/hvdctransmission/>.
- [106] "HVDC Grid Feasibility Study," CIGRE TB 533 - Working Group B4.52, January 2013.

- [107] "An Introduction to High Voltage dc Networks," Pacific Northwest National Laboratory, February 2014. [Online]. Available: <https://certs.lbl.gov/sites/all/files/kirkham-introduction-to-high-voltage-dc-networks.pdf>.
- [108] J. Pan, K. Srivastava and T. Jonsson, "AC grid with embedded VSC-HVDC for secure and efficient power delivery," in Energy 2030 Conference, 2008, Atlanta, 2008.
- [109] H. Xiao, K. Sun and Y. Liu, "Operation and Control of Hybrid HVDC System with LCC and Full-bridge MMC Connected in Parallel," IET Generation, Transmission & Distribution, vol. 14, no. 7, pp. 1344-1352, 2020.
- [110] K. Sun, H. Xiao and Y. Liu, "A Station-hybrid HVDC System Structure and Control Strategies for Cross-stream Power Transmission," IEEE Transactions on Power Systems, 2020.

APPENDIX A. R&D Recommendations from Previous Reports

DOE Grid 2030 – A National Vision for Electricity’s Second Hundred Years”

The 2003 DOE “Grid 2030 – A National Vision for Electricity’s Second Hundred Years” based on inputs from industry leaders, developed a national vision of the future electric system:

“Grid 2030 is a fully automated power delivery network that monitors and controls every customer and node, ensuring a two-way flow of electricity and information between the power plant and the appliance, and all points in between. Its distributed intelligence, coupled with broadband communications and automated control systems, enables real-time market transactions and seamless interfaces among people, buildings, industrial plants, generation facilities, and the electric network” [85].

Following the development of the vision, a similar group of industry leaders defined the National Electric Delivery Technology Roadmap (2004), the roadmap for achieving the Grid 2030 vision. Table A-1 defines the technologies, challenges, and RD&D needed for each of the areas presented in the National Electric Delivery Technology Roadmap [86].

Table A - 1. Technology Roadmap 2004 Critical Technologies, Challenges, and RD&D Recommendations

Technology Area	Top-Priority RD&D Needs
Advanced conductors	Advanced conductor materials and advanced conductor designs for high-current carrying capacity, low line losses, low-cost manufacturing, installation, and maintenance
High-temperature superconductors	<ul style="list-style-type: none">• Manufacturing scaleup of second generation high-temperature superconductor wire• Development of high-temperature superconductor cables, conductors, transformers, enabling equipment, and fault-current limiters• Basic research to identify higher temperature superconducting
Electric storage	Novel electric storage systems and manufacturing processes for lower costs and improved performance
Distributed intelligence and smart controls	<ul style="list-style-type: none">• Hardware, software, sensors and algorithms, and data acquisition and management systems for real-time communications and controls between operators and electricity devices• Communications standards/protocols for interoperability of distributed energy resources and grid interconnections
Power electronics	<ul style="list-style-type: none">• Power electronics for integrating distributed energy resources into grid operations• Power electronics including switchgear, fault current limiters, and static volt-amp reactive compensators• Advanced materials for power electronics devices to increase durability, efficiency, and reliability, and to lower costs• Customer and utility distributed energy devices and combined heat and power systems

Massachusetts Institute of Technology (MIT) Grid of the Future Report (2011)

In 2011, the Massachusetts Institute of Technology (MIT) conducted a similar exercise in defining the challenges and opportunities for the future electric grid for the next 20 years, thus aligning with the

Grid 2030 vision and roadmap developed by DOE. Table A-2 summarizes the challenges and opportunities identified by the MIT study focusing on the transmission system [87].

Table A - 2. MIT Grid of the Future Challenges and Opportunities.

Technology Area	RD&D Areas
Transmission system	<ul style="list-style-type: none"> • Energy management systems integrating phasor measurement units • Advanced control schemes • Flexible alternating current transmission systems • Information and communication • Interregional transmission planning • Transmission planning methods

Although developed years apart, the DOE reports and the MIT report reflect similar themes in challenges and technology RD&D needed to advance the grid to 2030 and beyond.

DOE Quadrennial Technology Review (2015)

In September 2015, DOE published the latest Quadrennial Technology Review, which examines the status of the science and technology that are the foundation of our energy system, together with the research, development, demonstration, and deployment opportunities to advance them [80].

The grid challenges or drivers—including aging infrastructure, changing demand loads, smart technology integration, the need for higher reliability and resilience, complex infrastructure, and the use of traditional technical approaches to managing the grid—make adapting to the rapidly changing environment necessitate new or continued innovation and RD&D at a scale and pace not achieved before. The 2015 Quadrennial Technology Review identified transmission RD&D needed to transform the grid of today to the grid of 2040 (Table A-3) [80].

Table A - 3. DOE 2015 Quadrennial Technology Review—Technology Transmission RD&D Focus.

Technology Area	RD&D Needs
Control Systems	<ul style="list-style-type: none"> • Dynamic and wide-area view: Grid measurements from a network of phasor measurement units. Need for advanced software tools/platforms that can fully use the vast amount information available • Fast and predictive analytics: Fast, predictive analytics for security events. Link to “real-time” situational awareness tools for evaluating risks and contingencies • System-wide coordination: N-1 reliability criterion may not meet reliability and resilience objectives. Emerging control system must coordinate resources across the entire system, from load to balancing area
Advanced Transformers	<ul style="list-style-type: none"> • Next-generation power transformers: Smaller, lightweight transformers that maintain or enhance reliability and efficiency. Low-loss magnetic cores and low-resistance windings, such as high-temperature superconductors • Solid-state distribution transformers: Solid-state distribution transformers can provide services for which current markets do not attribute a specific monetary value
Power Flow Controllers	<ul style="list-style-type: none"> • Low-cost flexible alternating current transmission systems: Cost with the use of power electronic devices limits flexible alternating current transmission system device use. New system designs and advanced power electronic devices to lower costs • High-voltage direct-current converters: improve the cost-effectiveness of variable renewable energy technology by increasing system efficiency. new designs, topologies,

Technology Area	RD&D Needs
	and advanced power electronic devices based on SiC or GaN, Research in modular multilevel converters
Protection Equipment	<ul style="list-style-type: none"> • High-voltage, direct-current circuit protection: High-voltage, direct-current protection systems to ensure reliability—reliable high-voltage, direct-current circuit breakers with matching power rating. Material and design innovations can drive down costs, increase power ratings, and accelerate technology deployment. multi-terminal HVDC networks require advanced methods for direct-current fault identification and location • Fault current limiters: Systems based on power electronic devices can also be used to limit fault currents, but the technology is still in development • Surge arresters: Improved surge arresters with dynamic abilities to withstand lightning strikes and lower costs for grid transmission components that use semiconductor devices
Advanced Cables and Conductors	<ul style="list-style-type: none"> • Overhead conductors: Innovations that exhibit lower resistance, are stronger and lighter, and have better thermal management can improve the performance of overhead conductors • Underground cables: Reducing the conductor resistivity, more power can be delivered through similarly sized cables. Advances in cable insulating materials can improve power rating and help dissipate heat more quickly to increase capacity • Advanced connectors: Connector design, surface modification to reduce oxidation, and improvements in contact strength and electrical resistance enhance system performance. Integration of sensors to monitor connector conditions can also increase system reliability and reduce the maintenance costs

The studies conducted between 2003 and 2015 defining grid RD&D needs demonstrate a continued need to increase or accelerate RD&D in areas of control systems, materials, sensing, communication- and cybersecurity, power electronics, system flexibility, and improved situational awareness across the entire system. The needs for RD&D in these areas and the pace at which these technology advancements are needed are increasing.

The Future of Electric Power in the United States (National Academies 2021)

The National Academies of Science, in collaboration with industry and universities published the “Future of Electric Power in the United States” report in 2021. This report encompassed a broad range of topics with the goal of identifying technical, social, and economic drivers that may alter the state of the power grid. These challenges are summarized in Table A-4.

Table A - 4. NAS Future of Electric Power in the United States—Technology Transmission RD&D Focus.

Technology Area	RD&D Needs
Power Electronics	<ul style="list-style-type: none"> • Technology can add fast, efficient, and accurate active control mechanisms to what has traditionally been a passive grid. It can make much greater use of HVDC feasible and provide the interface between the grid and new forms of renewable energy and energy storage • Support the development of new devices such as compact high frequency power transformers • These fast-moving technology areas will need sustained research investment, as well as the development of effective translation mechanisms to reach commercially relevant scale
Communication	<ul style="list-style-type: none"> • Wireless Technology <ul style="list-style-type: none"> ○ The future electricity grid, being a primary application domain for IoT technology can benefit greatly from these advances better-enabling functionalities such as power balance using inverter coordination, provided cost effective integration with grid operating systems can benefit greatly from these advances better-enabling

Technology Area	RD&D Needs
	<p>functionalities such as power balance using inverter coordination, provided cost effective integration with grid operating systems.</p> <ul style="list-style-type: none"> ○ Largely deployed to provide capacity where population is concentrated. This means that there can be coverage gaps, particularly in rural and remote areas where power systems may still need to operate. Therefore, other communications technologies may also be critical to the increased cyber sophistication of the electricity grid ● Internet of Things Technology <ul style="list-style-type: none"> ○ Success of using the IoT platform for grid operation relies on the successful development and implementation of the emerging generation of wireless technology ○ Advances in communications technologies will likely be needed to guarantee system performance, while limiting new vulnerabilities and operating in the face of technology migration and obsolescence
Sensing and Monitoring and Protection	<ul style="list-style-type: none"> ● Much of this represents mature technology, integration of sensing and autonomous control into these devices can further enhance system reliability and resiliency ● Asset monitoring across the transmission and distribution system using remote monitoring and UAVs and low-cost sensor networks that provide visibility and advanced analytics across network. ● Cost-effective advanced protection, both for DC and AC systems, including solid state breakers and breakers that can dynamically modify their protection regimes based on operating conditions, and potentially fault current limiters that can manage fault currents at distinct points on the AC and DC systems

Public Policy and Changes in Electricity Sector over last 10 Years

During the past 10 years, the electricity sector in the United States has experienced unprecedented changes. For example, in 2015, natural gas surpassed coal as the leading source of energy for generating electricity. In 2019, the contribution from renewable sources to electricity generation exceeded coal's contribution for the first time since before 1885, and the 966 terawatt-hours of electricity generated by coal plants in 2019 was the lowest amount since 1976 [88]. Between 2009 and 2019, the cost of wind and utility-scale solar photovoltaics declined dramatically. Although the rate of cost decline has slowed down with time, especially for onshore wind, capital costs reductions for these technologies are expected to continue to occur in the future [89].

Thirty states and the District of Columbia have developed renewable portfolio standards, which require that a specified percentage of the electricity that utilities sell comes from renewable resources [90]. Therefore, utilities are starting to embrace and implement plans to meet or exceed these standards. For example, 24 power companies, including Duke Energy Corp. and Southern Co., have committed to achieving net-zero emissions by 2050 and have eliminated plans to build new coal-fired power plants [91]. Arizona's biggest utility, Arizona Public Service, recently announced its own plan to achieve carbon-free energy by 2050, despite the lack of a state mandate requiring such a transition [92]. Colorado has outlined plans to get half of its power from renewables by 2030 and 90% by 2050, while multi-state utility Xcel Energy has committed to 100% carbon-free electricity by 2050.

The electrification of end-use services, the proliferation of distributed energy resources, and increases in growth in the adoption of electric vehicles recently has and will continue to be important considerations for the future operation of the grid. These changes over the last 10 to 15 years are

expected to occur more rapidly and because of this increased rate of electrification, we have likely crossed the point of no return for the electrification of transportation in the United States.

Additionally, as more edge technologies and smart systems are used, security vulnerabilities become more prevalent requiring more vigilance in adopting appropriate measures to protect the infrastructure.

The objective of this report is to identify technology gaps, challenges, and R&D opportunities for developing a reliable and resilient grid of the future in light of the aforementioned trends. These challenges are summarized in Table A-5.

Table A - 5. Challenges of the Future Grid.

Challenges	Transmission Component Impacts
More variable renewable and DERs	<ul style="list-style-type: none"> • Line congestion during large swings in power generation • More susceptible to instability due to lower system inertia and reduced frequency response • Greater transfer capacity needed • Increased harmonics
Fast rate of system changes with slow grid infrastructure upgrades	<ul style="list-style-type: none"> • Custom designs because of concerns with backward compatibility • Conservative upgrades because of uncertainty in need and location
More frequent and extreme/abnormal weather events and physical attacks	<ul style="list-style-type: none"> • Higher frequency of damage and disruptions from wind and ice • Higher operating temperatures during heat waves and rapid aging • Unpredictable points of failure
Greater reliance on information and communication technologies	<ul style="list-style-type: none"> • Susceptibility to cyberattacks and electromagnetic pulses • Synchronized timing (GPS) and component awareness needed
Greater environmental constraints and desire for sustainability	<ul style="list-style-type: none"> • Restrictions on insulation and cooling materials • Limited right-of-way for new infrastructure investments

APPENDIX B. Scenario Analysis

Distributed Scenario

Since Westinghouse began building the modern AC electric grid in the United States more than 120 years ago, the primary function of the transmission system has been to move energy from bulk generation power plants to the point of use while maintaining a stable, reliable system. Bulk generation plants typically have multi-megawatt to gigawatt capacities and are often located great distances from load centers. Historically, bulk generation plants have had large, rotating masses and powerful magnetic fields, and these properties have been leveraged heavily in the design, control, and operation of the power system.

In a distributed scenario, loads are increasingly served locally through the distribution or sub-transmission system from smaller, generally inverter-based distributed resources. These generators typically have neither the inertia nor the magnetic fields associated with their bulk counterparts. Because the generation is located at the point of consumption, the need for moving energy over great distances is diminished, and distribution utilities will rely less on transmission utilities and bulk generators to supply load. As a result, fewer bulk generating plants are required, and energy moved over transmission lines is significantly reduced overall.

Numerous drivers are pushing toward a more distributed grid. As intermittent resources such as wind and solar become more common, traditional base-load plants such as coal and nuclear become less economically attractive. Utility customers are transitioning from passive consumers to active customers. Falling costs of both DERs and distributed storage are driving customers and utilities in search of resiliency, reliability, and congestion relief to consider these non-wire alternatives. Technological advances and more educated consumers are creating grid-interactive loads with the ability to consume electricity intelligently.

The paradigm shift from a centralized, bulk generation architecture to a more distributed architecture has many implications, particularly when coupled with a shift from rotating machines to inverter-based generation. Traditional protection schemes that rely on overcurrent and negative sequence components are already becoming less common, and communication-assisted methods are becoming more common. The operational complexity of a fully distributed architecture would increase this dependence on communication and demand model-driven and ML-based approaches to protection.

The transmission infrastructure needs in a distributed scenario will largely depend on the role of the transmission system in this future. If the transmission system is to remain the glue that holds the electric system together, significant research will be needed to ensure the transmission system can accomplish this function with limited use of base-load plants. In cases in which local load and generation are not well aligned (e.g., day-time generation from solar on a system with an evening peaking load), transmission systems may need to be able to handle the reactive power needs of very lightly loaded and very heavily loaded lines.

In this scenario, challenges to the transmission system infrastructure include the following:

- Planning challenges related to increase in distributed generation that is not governed by transmission/bulk generation regulations
- Decreased revenue for transmission system owners/decreased need for new transmission lines (i.e., change in business model)
- Responsibility to maintain system stability and reliability with reduced base load
- Unbalance, volatility, and other transmission impacts from distributed generation
- High relative need and flexibility of reactive power compensation

Transmission technologies/research that could address these challenges (this will help shape the outline for the technology areas to consider) include the following:

- Improved transmission/distribution simulation
- Advanced adaptive protection schemes
- Networked microgrid control schemes
- Distributed power flow devices
- Advanced dynamic reactive power sources

Major Manufacturing back to the United States Scenario

If major manufacturing comes back to the United States in the next 10 to 20 years, new challenges will be brought to the electric power industry and may significantly affect the transmission infrastructure.

Although the manufacturing industry keeps pursuing better energy efficiency and sustainability, the overall electricity consumption increase can be substantial if the scale of the growth in manufacturing is large enough. Local load may spike rapidly at some manufacturing centers as manufacturers come back, which adds uncertainty factors to the mid to long-term transmission planning. The transmission capacities may be exhausted by the load growth due to the inaccurate planning. Additionally, the advances in logistic and communication sectors may further relax the geographical restrictions on the supply chain of manufacturing in the future. The manufacturing supply chains are not necessarily aggregated in terms of geographic location. Electric loads at manufacturing centers may be closely correlated with loads (of the supply chains) that are well distant from them. It brings challenges to load prediction, dispatch operation, and transmission planning.

Fusion with the data and AI technologies is changing the energy (i.e., electricity) consuming characteristics of the manufacturing industry. Manufacturing is expected to be more customer-centric, and thus more customized and personalized in the future. The make-to-order strategy will be favored by more and more manufacturers, which will likely make their electricity consumptions more intermittent and difficult to predict.

The types of manufacturing should also be considered when estimate the impacts. The high energy density manufacturers such as the mass chemical and metal producers are often electric loads with low power factors. Reactive power compensation and system protection may be stressed out if the coming back of those manufacturers are not well planned and prepared. Related regulations may need to be updated accordingly.

In this scenario, challenges to the transmission system infrastructure include the following:

- Good predictions to the scale, type, location of manufacturing growth, and their electricity consumptions
- Challenges to mid- to long-term transmission planning due to the uncertainties of the manufacturing growth
- The intermittent load patterns of future mass manufacturing set difficulties to load prediction and dispatch/operation
- Exhausted transmission capacity
- Correlated load behaviors over wide geographic areas
- Low power factor loads (inductive loads) bringing challenges to reactive power compensation and related regulations

Transmission technologies/research that could address these challenges (this will help shape the outline for the technology areas to consider) include the following:

- Advanced load estimation and prediction technologies (data/AI-based) for better transmission planning and operation
- Transmission line uprating technologies (e.g., high-temperature conductor, high-emissivity coating for increasing transmission capacity in relatively short period of time
- Advanced dynamic rating of transmission lines and transformers to improve the use rate of existing lines
- Advanced reactive power compensations to accommodate low power factor loads
- FACTS and other advanced power flow control
- Microgrid and energy storage to reduce the burden of power transfer

Volatile—Cyber Physical, Attacks, EMPS

As the national interconnected electric grid becomes increasingly dependent on computers and data sharing—providing significant benefits for utilities, customers, and communities—it has also become more vulnerable to physical and cyber threats. With attackers learning and developing, defenses for all types of critical infrastructure control systems, including water, gas, and transportation, must improve to keep pace. The North American Electric Reliability Corporation defines a bulk electric system cyber asset as that if rendered unavailable, degraded, or misused would (within 15 min of its required

operation) mis-operation, non-operation, or adversely impact one or more facilities, systems, or equipment, which, if destroyed, degraded, or otherwise rendered unavailable when needed, would affect the reliable operation of the bulk electric system [1] [2]. Physical- and cybersecurity of transmission facilities is very difficult because of their complexity and homogeneity. A huge part of the system is connected to the internet, so remote control is possible. Industrial control systems are applied in various forms (e.g., all bulk power systems use energy management system/SCADA architectures for remote control). A well-structured defense mechanism against cyber threats can only be effective if the whole power grid is deeply known by its industrial control system. Therefore, SCADA structures integrated into each other should be examined. This approach can be effectively used in developing a new test bed for cyberattack impact analysis against vulnerable transmission facilities. SCADA is a distributed architecture that is responsible for data collection and system control. On the contrary, the energy management system is a system that provides all the necessary data management and calculations. In terms of the research, SCADA systems are the key to creating a connection to the whole smart power grid. Nuclear EMP attacks are another concern. An EMP is a high-intensity surge of energy that can disrupt or destroy electronics by essentially overloading them. A natural solar superstorm, known as a “geomagnetic disturbance,” has about a 10% chance of occurring every decade according to NASA [93]. There are concerns that an EMP triggered at the right altitude could bring down the U.S. transmission grid as well as other critical infrastructures such as telecommunications, emergency services, and hospitals.

Technology Solutions

Prevention strategies can be applied. One prevention strategy is to retrofit critical grid equipment with analog and manual technologies as a defensive measure against foreign cyberattacks that could bring down critical transmission facilities. The idea is to use “retro” technology to isolate the grid’s most important control systems to limit the reach of a catastrophic outage. Specifically, it would examine ways to replace automated systems with low-tech redundancies, such as manual procedures controlled by human operators. While evolving standards with strict enforcement help reduce risks, efforts focused on response and recovery capabilities are just as critical—as is research aimed at creating a well-defended next-generation smart grid. Another solution could be the use of infrared technology. Infrared sensors can be installed on all high-voltage transmission lines. Drones can then be used to patrol critical lines and facilities.

APPENDIX C. Future Scenarios

Figure C-1 shows the energy flows diagram for the United States in 2019 [52]. These diagrams are useful to illustrate how energy resources, and their transformation into electricity, are used by the transportation, industrial, residential, and commercial sectors. The width of the arrows in these diagrams is proportional to the corresponding amount of energy, which is indicated by the numerical values (in quads).

Figure C-1 shows that natural gas was the largest source of energy (11.7 quads) for electricity generation in the United States in 2019. The diagram also shows that the largest consumer of electricity was the residential sector (4.9 quads) followed by the commercial, industrial, and transportation sectors. For the transportation sector, 0.03 quads of electricity were used by public mass transit systems and by the 1.5 million electric vehicles on U.S. roads [94].

Energy flow diagrams are also useful to illustrate potential future scenarios and frame discussions about what the electric grid of the future would look like under those scenarios. Figure C-2 shows the estimated balance of power supply and demand for each region of the country by 2030 [95]. The map shows that some regions (notably the Upper Midwest and Texas) will be producing substantially more electricity than they will consume, while others (notably in the West and Northeast) will consume much more than they produce [96], [95], [97] and also shows one of many possible scenarios for the United States in 2030. For example, in this case, the contribution of coal to generate electricity is expected to be almost nonexistent, while renewables constitute the largest source of energy for electricity production. It has been assumed that the energy efficiency of buildings, and the industrial and commercial sectors, will increase by 10% compared with 2019, and that 50% of the highway fleet is electrified, thus increasing the overall efficiency of the transportation sector from 21% (2019) to 60% (2030). It has also been assumed that the contribution of nuclear energy to electricity generation decreases from 99.3 GW (2019) to 79 GW (2030), with the addition of new modular nuclear power plants partially offsetting the expected retirement of light water reactors from the current fleet. This is a consequence of the very large capital costs associated with building gigawatt-class nuclear power plants [98].

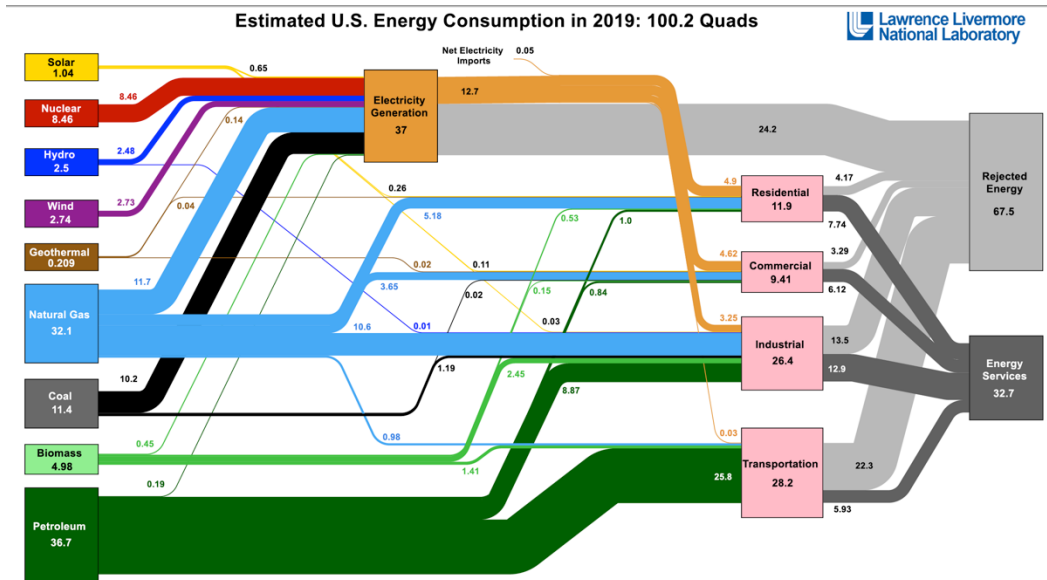


Figure C - 1. Energy flow diagram for the United States in 2019.

Source: Lawrence Livermore National Laboratory

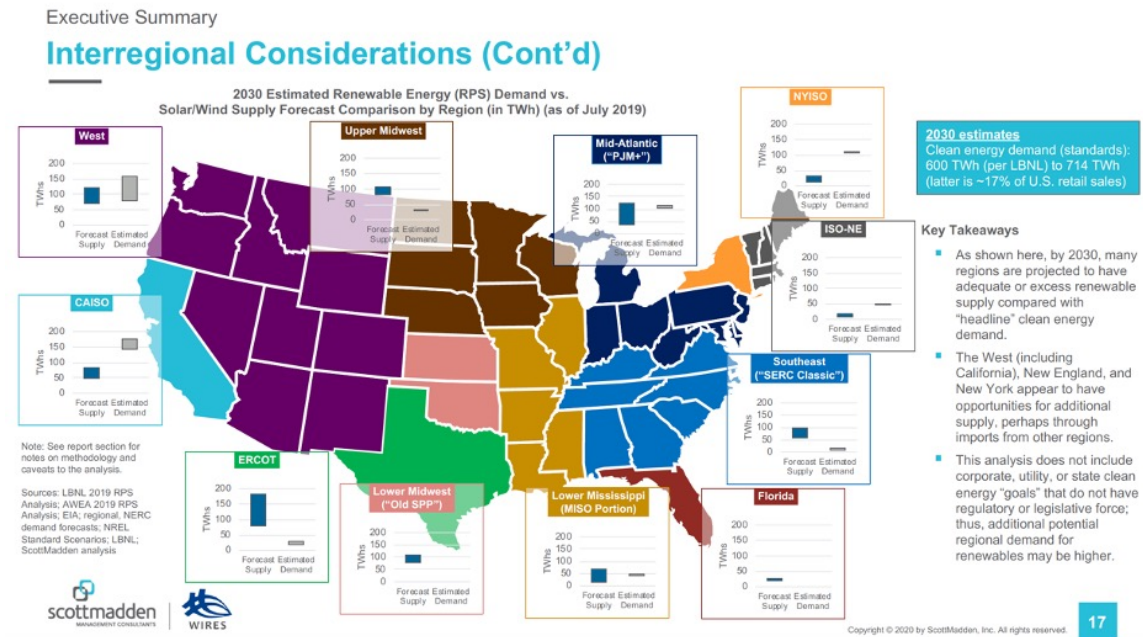


Figure C - 2. Estimated 2030 balance of power supply and demand for each region of the United States [95].

The energy flow diagrams in Figure C-1 and Figure C-2 provide information at the national level and therefore lack granularity associated with the operation of the regional grids. This is relevant because the areas of the United States with the most renewable energy potential are not necessarily those that need the most electricity. A report from the Wind Energy Foundation found that the 15 states between

the Rocky Mountains and the Mississippi River—Montana, Wyoming, Colorado, New Mexico, North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, Texas, Minnesota, Iowa, Missouri, Arkansas, and Louisiana—account for 87% of the nation’s total wind energy potential and 56% of its utility-scale solar potential but are only projected to account for 30% of the nation’s energy demand in 2050 [96].

One way to balance this supply-demand imbalance is to connect these regions with HVDC transmission lines. Although HVDC lines are more expensive, they can carry more power with less losses than AC lines, so they would be preferred for transmitting power over long distances. The more each region can import and export electricity, the more it can balance its own fluctuations in supply and demand with its neighbors’, therefore maximizing the use of renewable energy [95].

Another benefit of moving away from a regionally divided electricity sector to a national system would be greater resiliency. As the Scott Madden report shows, various regions of the country can (during severe weather events) face fuel shortages, transmission congestion, and even rolling blackouts. If nothing else is done, the coming retirement of many coal plants will exacerbate these vulnerabilities [96].

The best way to build resiliency against these events, which are increasing in frequency because of climate change, is to connect the regions of the country into a single national grid, so that regions facing difficulty can draw power from neighbors experiencing an event.

According to a 2016 study by MacDonald and Clack, an additional benefit of an interconnected national system enabled by HVDC transmission is the possibility of reducing carbon dioxide emissions from the electricity sector by up to 80% relative to 1990 levels [99]. These findings are consistent with those of the 2018 Interconnections Seam Study, which also identified the costs and benefits of stitching together America’s fragmented grid [100], [101]. All the scenarios considered in the Interconnections Seam Study meet demand and reliability requirements, make energy trading more efficient, smooth-out fluctuations in supply and demand, and reduce the cost of electricity enough to more than pay for the costs.

As part of its Belt and Road Initiative, the government-owned utility State Grid of China is developing a super-grid with the ultimate objective of swapping energy across borders in Asia [102]. As discussed previously, the benefits of large networks include enabling fluctuating renewable sources such as wind and solar to generate a far larger share of the electricity. Long, high-capacity transmission lines make it possible to balance out the dimming sun in one time zone with wind, hydroelectric, or geothermal energy several zones away. State Grid has also developed software that can precisely control the voltage and frequency arriving at destination points throughout the network, enabling the system to react rapidly and automatically to shifting levels of supply and demand [101]. Already, State Grid has built three of the world’s longest power transmission lines in Brazil [103].

Politics and bureaucracy have stymied the deployment of modern power grids in much of the world. In the United States, it can take more than a decade to secure the necessary approvals for the towers, wires, and underground tubes that cut across swaths of federal, national, state, county, and private

lands—on the rare occasion that they get approved [101]. One potential solution to objections that high-voltage transmission lines affect the landscape is burying transmission lines underground.

A severe constraint when these cables are used for AC transmission is that the high capacitive charging current required generally limits their length to just tens of miles. DC cables are limited only by electrical losses [87]. Despite innovations in insulation materials, the complexity of assembling and installing cables means that cables will remain more expensive than overhead lines. However, the difficulty of siting overhead lines in the United States can make underground cables an attractive option in some areas despite the greater expense [101]. Recent developments with boring technology could enable the fabrication of lower-cost underground tunnels for housing high-voltage transmission lines [104]. Figure C-3 shows an example of these recent boring technologies in practice.



Figure C - 3. Underground tunnels in London for power distribution [National Grid].

HVDC Overlay in the U.S. Transmission Grids

Given the increase in renewable generation in recent years and decades forward, it has become increasingly important to upgrade the U.S. transmission grids to facilitate reliable and efficient integration of abundant renewable energy resources across the country. With the existing transmission grid infrastructure, upgrading the delivery capability and flexibility is challenging with conventional AC expansion options. AC expansion options are often limited by voltage or transient instability issues and impacts of uncontrollable loop flows. HVDC technologies are advanced expansion options for grid enhancement and modernization to mitigate the challenges resulting from high penetration of renewables and diversified power flow patterns [105]. In the United States, several HVDC projects are in the planning pipeline to facilitate integration of renewable resources in remote host regions to distant load centers. Also, several proposed HVDC projects aim to increase inter-regional or intra-

regional power transfer capabilities and mitigate network congestions. The recent interconnections seam study by national laboratories, leading academics, and industry partners has evaluated expansion options for upgrading the U.S. transmission grids for high renewable future scenarios [100]. The study results highlighted the urgent need for the cross-seam transmission systems using HVDC technologies to achieve significant economic benefits, such as more efficient development and use of wind and solar energy resources, maximizing the values of load diversity, and frequency response reserves sharing between regions and interconnections.

In view of the increasing number of planned and proposed HVDC projects and the growing penetration of renewable energy resources, the future U.S. transmission infrastructure development will clearly go in the direction of a hybrid AC/DC grid structure to enable resilient, efficient, and flexible power delivery. Most existing HVDC schemes have been realized as point-to-point connections, but the scope of future HVDC development will evolve from typical two-terminal links toward multiterminal configurations for increased connectivity and operational flexibility. HVDC grids technically are feasible [106], although more R&D is needed on the key enabling technologies such as DC/DC converters and HVDC circuit breakers. From a system topology perspective, a multiterminal system is typically in simple radial topology whereas an HVDC grid may have a relatively complex topology, including a networked DC loop [107].

Figure C-4 shows the envisioned future HVDC systems, which might be developed and integrated with the underlying U.S. transmission networks. These envisioned future HVDC systems together with the existing HVDC systems collectively form the HVDC overlay of the U.S. transmission grids. Conceptually, the HVDC overlay of the U.S. transmission grids would comprise of cross-seam interconnections that interconnect the three asynchronous Interconnections (Eastern, Western, and Electric Reliability Council of Texas), inter-regional connections and intra-regional connections [108], as well as potential offshore backbone systems off the east coast.

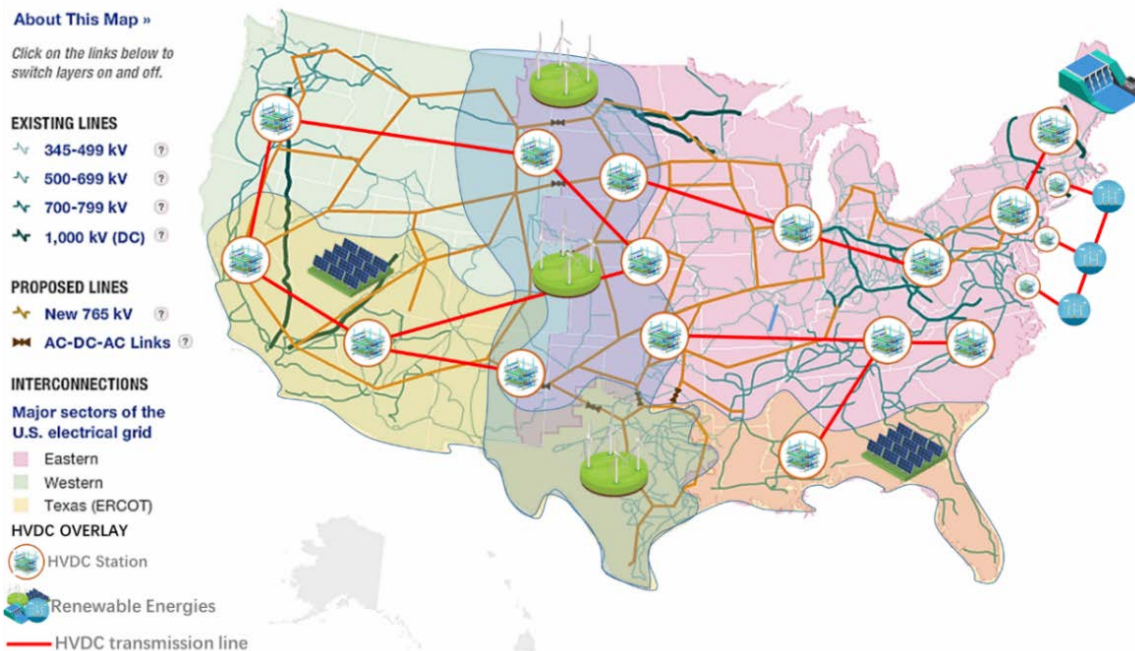


Figure C - 4. Concept of the HVDC overlay.

Two basic converter technologies are used in modern HVDC transmission systems, including classical LCCs and self-commutated VSCs. LCC-HVDC transmission is mainly used for bulk power delivery through long distance overhead lines where the power flow is typically unidirectional or not frequently reversed. One of existing LCC-HVDC lines in the United States is the Pacific DC Intertie which currently operates at ± 520 kV and transfers up to 3,220 MW power between the North subregion and the South subregion of the Western Interconnection. The typical capacity ratings of installed LCC-HVDC systems are between 3 and 6 GW while the highest capacity rating has reached 12 GW. VSC-HVDC transmission systems can rapidly control both active and reactive power independently within its rated capacity range and reverse power flow direction quickly. VSC-HVDC systems can transmit power underground, underwater, and through overhead lines. The typical capacity ratings of installed VSC-HVDC systems are from a few hundred megawatts to 1 GW or higher. With recent technology advancements, VSC-HVDC systems can now be used for power transmission up to 3–4 GW at ultrahigh voltages. VSC-HVDC converter technologies are under continued development for higher voltage, higher efficiency, modular products, and compact structure that will provide more flexibility.

Both LCC-HVDC and VSC-HVDC are considered as basic technologies for the development of the HVDC overlay in the U.S. transmission grids. The choice of LCC-HVDC and VSC-HVDC for long-distance interconnections will depend on system and functionality requirements and comprehensive system studies from both cost and performance perspectives. In general, VSC-HVDC technologies are more suitable for implementing multiterminal systems and have many merits for inter-regional and intra-regional connections as well as offshore backbone systems. Considering the trade-off between the investment and functionality, hybrid HVDC technologies could be a prospective solution for the

development of HVDC overlay. Hybrid HVDC technology combines the advantages of VSC and LCC technologies to optimize system designs toward lower costs, enhanced functionality and robust performance. Generally, the hybrid HVDC systems can be divided into three types: (1) pole-hybrid system, (2) terminal-hybrid system, and (3) converter-hybrid system [109]. A pole-hybrid HVDC system is a bipolar system in which one pole adopts LCC and the other pole uses VSC. In a terminal-hybrid HVDC system, one terminal adopts LCC and the other adopts VSC. The converter-hybrid HVDC system uses converters that are formed with LCC and VSC in series. Recent research has investigated the feasibility of station-hybrid HVDC system wherein each terminal is composed of parallel connected LCC and VSC [110]. The station-hybrid HVDC systems and control strategies can be extended to hybrid multiterminal HVDC systems comprising VSC, LCC, and hybrid converter stations.

Within the context of the U.S. transmission grids, research and studies are needed on practical HVDC overlay concepts and implementation strategies. It is also necessary to investigate the feasibility and benefits of hybrid HVDC technologies and their potential applications for developing HVDC overlay in U.S. transmission grids. Additionally, advanced wide-area monitoring, control, and protection methods for hybrid AC/DC transmission grids need to be further developed to ensure resilient and efficient grid operations under highly uncertain supply and demand conditions and diversified power flow patterns. Finally, a need exists to develop intelligent and adaptive controls for HVDC links to improve the stability and resilience of the future U.S. transmission grids in response to different grid disturbances.

APPENDIX D. Some Promising DC Circuit Breaker Designs

Table D - 1. Promising DC Circuit Breaker Designs

DC circuit breaker type		Mechanisms	Advantages	Disadvantages
Mechanical	Passive resonance	<ul style="list-style-type: none"> • Mechanical main switch • Passive LC resonance branch in parallel with main switch 	Simple, reliable	Slow operation
	Current injection by pre-charged capacitor	<ul style="list-style-type: none"> • LC resonance branch controlled with a commutation switch • A pre-charge circuit to charge the capacitor 	Faster than the passive resonance design	Needs time to charge capacitor between operations
	Active resonance	<ul style="list-style-type: none"> • A converter (e.g., a full-bridge VSC) to excite the LC resonance 	Fast and controllable excitation of the resonance	Cost increased because of the converter
Hybrid	Classic configuration	<ul style="list-style-type: none"> • An ultrafast switch and a load commutation switch to conduct load current • Thyristor or insulated-gate bipolar transistor modules to form main breaker • Surge arresters for limiting voltage and dissipating energy 	Fast, low conduction losses	High cost because of semiconductor modules, lower reliability than other breaker types
	Variants of classic configuration	<ul style="list-style-type: none"> • A thyristor- and transformer-based commutation drive circuit to replace the load commutation switch • Bidirectional type using full-bridge breaker to allow bidirectional current flow • Thyristor-based graded voltage path as main breaker • An H-bridge combined with surge arresters to replace main breaker and energy dissipating branches 	Improved operation time or reduced semiconductor costs depending on specific design, low normal conduction losses	More complex, lower reliability than other breaker types
	Inductive coupled configuration	<ul style="list-style-type: none"> • Transformer between conduction and breaker branches to replace load commutation switch 	fewer semiconductor modules than other breaker designs	Difficult to determine optimal values of coupling inductance and ratio

DC circuit breaker type	Mechanisms	Advantages	Disadvantages
	and initiate current commutation		
Auxiliary capacitor	<ul style="list-style-type: none"> • A pre-charged capacitor integrated in a commutation circuit to divert current to the breaker branch 	Fast operation (<3 ms)	Operating at lower voltage
Superconducting commutation circuit	<ul style="list-style-type: none"> • A superconductor to replace the load commutation switch • Current commutation initiated by superconductor quench 	Very low conduction losses, fast commutation	Ultrafast switch opens at a residual (small) current
Gas discharge tube	<ul style="list-style-type: none"> • Gas discharge tubes to replace semiconductor-based main breakers 	Fast, cost significantly reduced, good modularity	Short cathode lifetime