U.S. DEPARTMENT OF ENERGY

Next-Generation Grid Technologies

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Executive Summary

The electric power system in the United States is massive, complex, and rapidly transforming. The grid was originally designed for large, centralized generation sources delivering power in one direction to consumers, but in recent years, several factors – such as customer demands, policy changes, and technology advancements – have driven the system to evolve. Increased demand for renewable resources, electric vehicles, distributed energy resources, and electrification ensure that the structural requirements of the future electric network will differ substantially from those of today's grid. Furthermore, governments (local, state, and federal) are setting increasingly aggressive targets for deep decarbonization of the economy. The Biden Administration has set a goal of a 50% emissions reduction by 2030, 100% clean electricity by 2035, and net-zero emissions by 2050 [1]. To meet these aggressive targets, the entire electric power sector must be dramatically upgraded, with improvements to grid infrastructure required to support this power sector transformation.

Through this transformation, the grid of the future faces many challenges. Extreme weather events, variability and intermittency from renewable generation sources and other advanced technologies, and cyber-security in an increasingly complex system are among the considerations stakeholders must prepare for. Combined with energy system trends, as seen in Table 1, these factors are facilitating a rapid evolution to many possible future architectures for the systems with which the U.S. generates, transmits, and distributes its electricity. The grid, as an ultra-large-scale system, may diverge regionally to different architectures, resulting in a future where different parts of the system may operate in vastly different ways than others. Policy, economics, technology readiness, and customer demand drive different architectural considerations across regions, and fundamentally, different technology requirements.

Table 1. Summarized Trends and Challenges

Source: U.S. Department of Energy, Office of Electricity

Trends	Challenges
➢ Transition to Low-Emission Generation Sources ➢ Increased Customer Participation in Grid Markets ➢ Integration of Digital and Communication Technology ➢ Rapid Electrification of Transportation and Buildings ➢ Emphasis on Grid Resilience	➢ Increasing Generation Uncertainty ➢ Aging Infrastructure ➢ Congestion ➢ Unpredictable Events & Disasters ➢ Cybersecurity

To solve the challenges and support the trends associated with ensuring a seamless transition to the future grid, technology solutions must be developed and deployed. While these technologies have great potential to solve the problems facing the future electric network, each has their own barriers to widespread adoption. The specific paradigm shifts of how these technologies are used and implemented in the grid are driving the transformation of the electric network to a technologically advanced future. Further R&D advances in the technologies that make up the system will be critical to building a future electric network that can support reliability and resilience goals, deep decarbonization, and other emerging needs of the system.

In this report, three transformative paradigms are emphasized, as shown in Figure 1: the shift from static line ratings to dynamic line ratings, from static networks to dynamic topology optimization, and from passive equipment to advanced power electronics. For dynamic line ratings and topology optimization, needed R&D includes improved software and modeling solutions, impact evaluation and demonstration projects to increase utility confidence, and enhanced workforce development. For power electronics, technical R&D is needed across advanced components, devices and systems, and whole-system integration. Each R&D opportunity helps solve the grid of today's challenges and facilitates the transformation to a modernized, future grid that is resilient, reliable, secure, affordable, flexible, and sustainable.

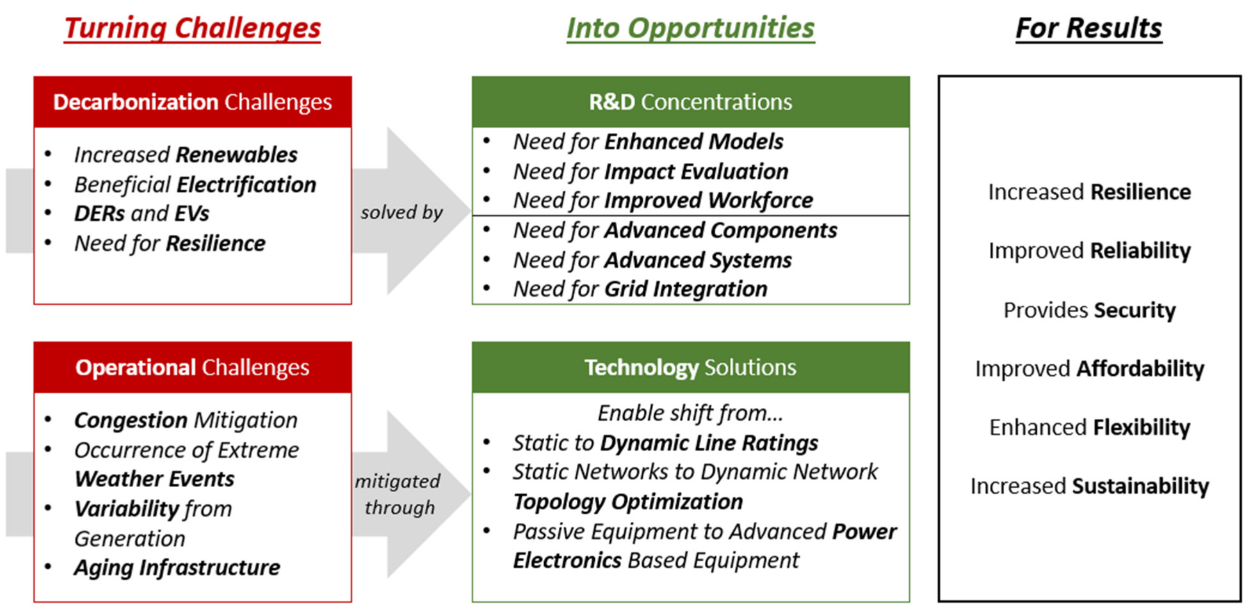

Figure 1. R&D areas of next-generation grid technologies.

Source: U.S. Department of Energy, Office of Electricity

Abbreviations

AAR	ambient-adjusted ratings
AC	alternating current
AGM	Advanced Grid Modeling
AI	artificial intelligence
ARPA-E	Advanced Research Projects – Energy
ASCE	American Society of Civil Engineers
BOS	balance of system
CAISO	California ISO
DC	direct current
DER	distributed energy resources
DLR	dynamic line rating
DOE	Department of Energy
EMS	energy management system
EPRI	Electric Power Research Institute
ERCOT	Electric Reliability Council of Texas
ESS	energy storage systems
EV	electric vehicle
EVSE	electric vehicle supply equipment
FACTS	flexible AC transmission system
FERC	Federal Energy Regulatory Commission
GWAC	GridWise Architecture Council
HPC	high-performance computing
HVDC	high-voltage direct current
IGBT	insulated-gate bipolar transistor
IPFC	interline power flow controller
ISO	independent system operator
ISO-NE	ISO-New England
MISO	Midcontinent ISO
MTDC	multi-terminal DC
MVA	megavolt-amperes
NAERM	North American Energy Resilience Model
NERC	North American Electric Reliability Corporation
NREL	National Renewable Energy Laboratory
NYISO	New York ISO
O&M	operations & maintenance
PE	power electronics
PEBB	power electronics building block
PFC	power flow controller
PJM	PJM Interconnection
PV	photovoltaics
R&D	research & development
ROE	return on equity

RTO	regional transmission organization
SCADA	supervisory control and data acquisition
SLR	static line rating
SPP	Southwest Power Pool
SSPS	solid-state power substation
STATCOM	static synchronous compensator
T&D	transmission & distribution
TRAC	Transformer Resilience and Advanced Components
ULS	ultra-large-scale
UPFC	unified power flow controller
XFC	extreme fast charging

Next-Generation Grid Technologies

Table of Contents

I. Introduction

The North American electric grid is often described as the most complex machine of the 20th century [2]. With a capacity of 1.2 million megawatts, delivering electricity to all customers across the United States' 600,000 circuit miles of transmission lines and 5.5 million miles of distribution lines, the massive bulk power system's importance cannot be overstated [3] [4]. As the climate crisis increases the frequency and intensity of unpredictable events that threaten the grid and cost stakeholders billions of dollars in damages, such as during the summer 2020 California wildfires and the 2021 Texas blackouts, grid modernization and resilience efforts become ever more critical. These efforts, performed across the various scales of electricity transport from generation to end-use, will help to ensure a modernized future electric network.

Figure 2 depicts a graphical view of the grid and its major components. Bulk generation sources, including fossil fuels (e.g., coal and natural gas), nuclear, and renewables (e.g., solar and wind), "flow" from the left across transmission and distribution architecture. Grid architecture includes physical infrastructure that delivers power temporally and spatially (i.e., from one place to another over time), and digital systems that control and manage the flow of information across the complex, networked electric system. End uses and end users include traditional utility customers, such as homes and businesses, and newer emerging sources such as electric vehicles (EV) and Distributed Energy Resources (DER) [5].

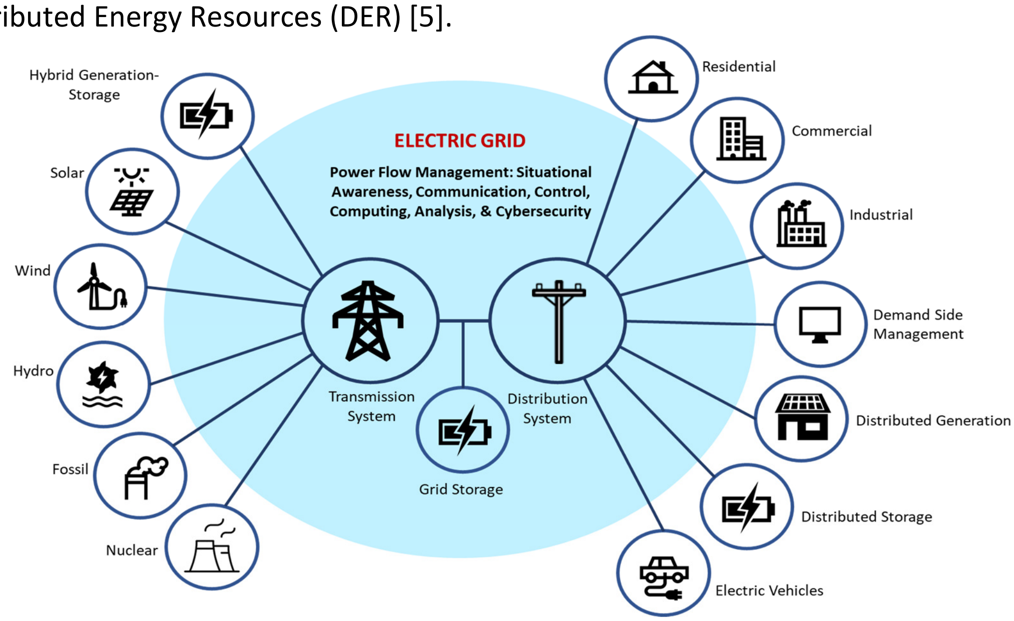

Figure 2. Major components of the electric grid.
Source: U.S. Department of Energy, Office of Electricity

This depiction illustrates that the electric network acts as an essential connector between new, emerging technologies such as solar, wind, EVs, and DER. Without a grid capable of integrating these technologies through advancements such as enhanced control, increased transmission capacity, prioritized workforce development, and comprehensive system modeling, such new technologies are not viable and are at risk to not meet customer demand. Appendix A: Grid Views shows several alternate views of the grid and its many connected layers, stakeholders, and considerations.

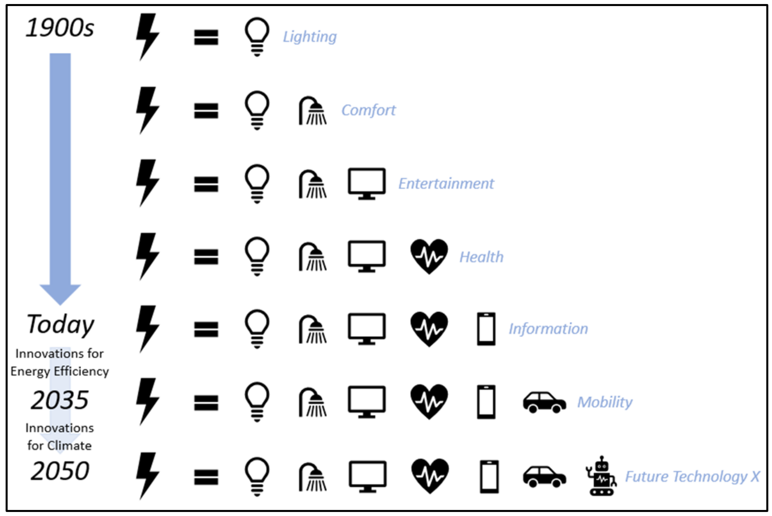

Figure 3. Uses of the grid over time.
Source: U.S. Department of Energy, Office of Electricity

While the electric network covers a wide range of essential applications, it has its origins in limited usage and patchwork solutions to solve immediate needs. The modern electric grid can be traced back to the late 1800s and early 1900s when electricity corresponded only to lighting and a few other services limited to industrial and other specialized applications [6]. Over time however, electricity has become essential to all parts of modern life, including healthcare infrastructure, communication, entertainment, and transportation. The grid has gradually evolved to meet these new use cases and challenges, but modern and future requirements place stress on parts of the grid that are required to act in a way they were not designed for. For example, the increase in distributed generation seen in the system today creates new difficulties with forecasting and load balancing caused by two-way power flows, while future demands such as the prospect of charging large fleets of EVs may cause even more significant operational challenges. Figure 3 summarizes the trajectory of the electric network over time, from its origins as a lighting system to the immense role it plays in all parts of life today. The number of services that the grid has provided over its lifespan is growing and will continue to grow as electricity impacts every aspect of the modern life [7].

The grid is a highly intricate system which is increasing in complexity as it also faces tremendous challenges. These challenges include the rapidly increasing penetration of renewable generation sources onto a grid that consists of aging hardware that was not initially designed for such sources. Security from external threats – both natural and manmade – also remains a priority for nearly every stakeholder, but resilience is difficult to maintain as grid infrastructure rapidly ages and trends towards expanding non-inertial generation. The trends and challenges faced by today's bulk power system illustrate the importance of grid modernization. Grid modernization addresses the problems facing today's electric network through the emphasis of six vital characteristics as defined by the U.S. Department of Energy: **Reliability**, **Resilience**, **Security**, **Affordability**,

Flexibility, and **Environmental Sustainability**[a] [8]. A modernized grid with these characteristics must also be equitable, where system benefits (including economic, health, and social) from advancements like clean energy access and energy-efficient housing and transportation extend to all levels of society regardless of race, ability, or socioeconomic status [9]. These grid modernization characteristics will be referenced throughout this report.

To achieve the characteristics of grid modernization, critical system challenges must be solved. Table 2 displays the main trends facing the system, caused by technology innovation, customer preference and government priorities, as well as key system challenges, caused by the listed trends and other future system requirements. Appendix B: Trends and Challenges Driving Transformation describes in detail some of the major trends and challenges that the future network must manage.

Table 2. Summarized Trends and Challenges

Source: U.S. Department of Energy, Office of Electricity

Trends	Challenges
➢ Transition to Low-Emission Generation Sources ➢ Increased Customer Participation in Grid Markets ➢ Integration of Digital and Communication Technology ➢ Rapid Electrification of Transportation and Buildings ➢ Emphasis on Grid Resilience	➢ Increasing Generation Uncertainty ➢ Aging Infrastructure ➢ Congestion ➢ Unpredictable Events & Disasters ➢ Cybersecurity

These paradigms, while described independently in Appendix B: Trends and Challenges Driving Transformation, represent a linear flow, with a causality demonstrating the path to a desired future grid. The requirements of the future electric network and other trends lead to difficult challenges, which are manageable through an array of technologies. However, implementing these technologies also comes with barriers and challenges, which are mitigated through prioritization of R&D programs in these areas.

Figure 4 displays advanced R&D enabling the electric network of the future as it solves the challenges of the future system.

[a] A reliable grid has high power quality and has few power outages with short durations; a resilient grid can recover quickly from an unforeseen event; a secure grid's critical infrastructure is protected from threats; an affordable grid minimizes costs for all customers; a flexible grid can respond quickly to uncertainty across many timescales; finally, a sustainable grid limits emissions and environmental impact through clean, efficient energy.

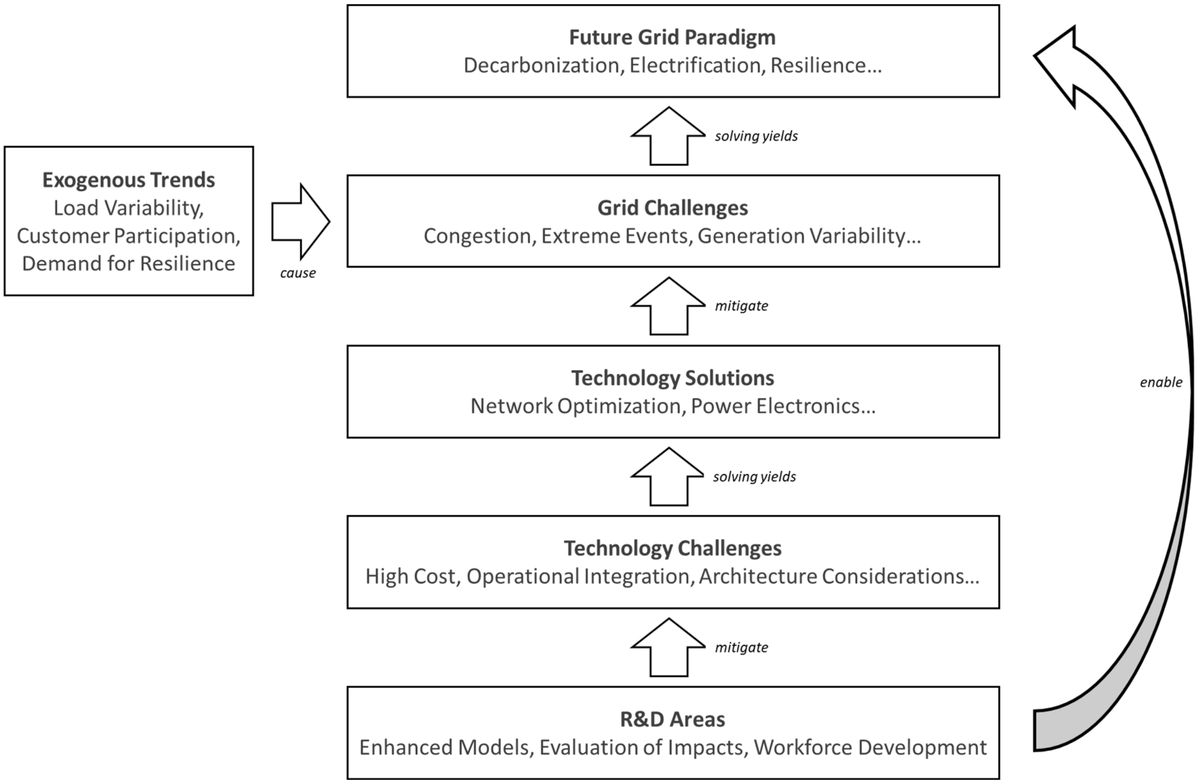

Figure 4. R&D impact on the future grid.
Source: U.S. Department of Energy, Office of Electricity

To facilitate the transition, advanced technology across all domains is implemented to achieve the six characteristics of grid modernization and meet the major challenges faced by today's electric grid.

Technology Solutions

The electric grid is undergoing a significant transformation. Many trends are driving this change, while challenges facing the grid raise significant concerns for all stakeholders. To solve these challenges and achieve the characteristics of grid modernization, numerous technology solutions have been introduced with many more still in development, each with their own benefits and limitations to provide functions useful for solving future challenges. For example, energy storage systems are deployed to aid in grid operations and power reliability[b] [10], active load management solutions will be useful to manipulate load shapes and incorporate more variable generation sources, advanced control and conductors help optimize power flow to reduce congestion, and power electronics will help with the rapid management of electricity in an increasingly bidirectional system. These are just a few examples of the grid-enhancing technology that provide functions and solutions to modernize the grid, and Figure 26 in Appendix A: Grid Views displays the network of technologies to do so.

[b] Energy storage systems represent a major opportunity for the grid, and worldwide energy storage markets are expected to increase 3-5x of 2020 levels by 2030.

Overcoming some of the barriers of grid modernization through technology is summarized in Figure 5. This figure is not meant to be exclusive or prescriptive, but instead demonstrate the varying potential of many technologies to solve the challenges previously outlined. Once the outlined problems are solved or mitigated, the electric network is far better equipped to support the future needs while maintaining reliability, resilience, security, affordability, flexibility, and sustainability.

	Increasing Variability	*Aging Infrastructure*	*Congestion*	*Unpredictable Events*	*Cybersecurity*
Enhanced Control	●	◓	●	◓	◓
Modeling and Analytics	●	●	●	◓	●
Sensors	◓	○	◓	●	◓
Energy Storage	●	◓	●	●	○
Power Electronics	●	◓	◓	◓	●
Advanced Conductors	◓	●	●	◓	○
Microgrids	○	◓	○	●	◓

● = Technology provides significant solutions to challenge ◓ = Technology provides some solutions to challenge ○ = Technology provides minimal solutions to challenge

Figure 5. Harvey balls chart for technologies and grid modernization characteristics.
Source: U.S. Department of Energy, Office of Electricity

A specific paradigm of technology transitions will be focused on in this report. The first is about the limits of system carrying capacity, and includes the evolution of line ratings, from static to dynamic and fast responding. The second transition is about system topology and optimization, from inflexible, firm grid topologies to ones that are variable and agile. The third area examines advanced design of system equipment, and the transition from passive hardware to dynamic power electronics that can facilitate and manage the evolving grid more effectively. Altogether, as summarized in Figure 6, these technologies support an integrated platform that enable future grid paradigms.

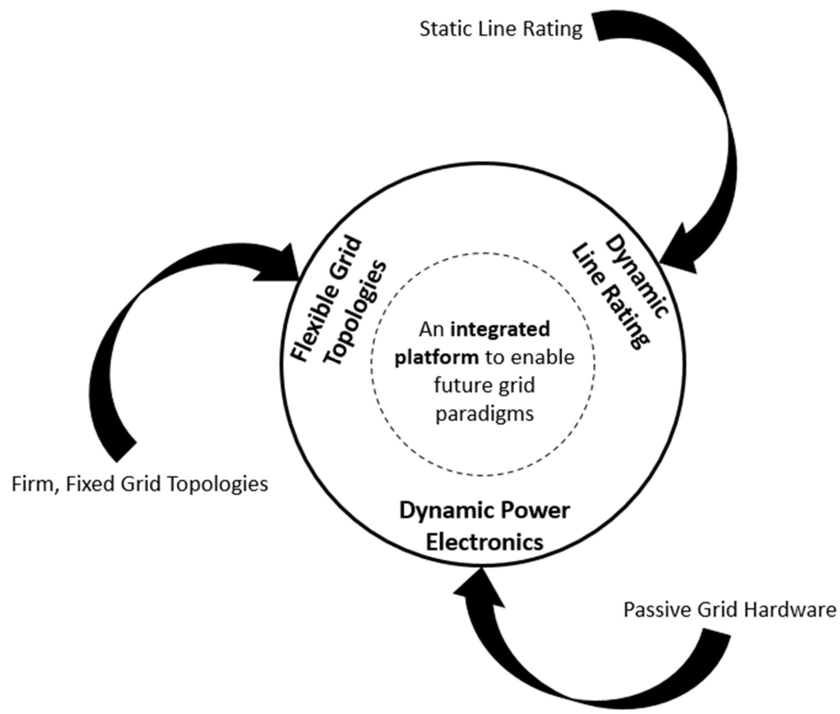

Figure 6. Vision and integration challenge of future technology paradigms.
Source: U.S. Department of Energy, Office of Electricity

II. Electric Network Optimization

While many technology solutions enable enhanced grid capabilities by adding elements onto the grid, there are some technologies, such as Dynamic Line Ratings (DLR) and Topology Optimization, that can be implemented without the need for significant hardware investments. These technologies, covered in this section, "unlock" parts of the network for potentially substantial efficiency improvements. For further reading, the 2020 *Advanced Transmission Technologies*[c] *Report* describes these technologies in greater detail.

[c] *Advanced Transmission Technologies* can be found at the following link: https://www.energy.gov/sites/prod/files/2021/03/f83/Advanced%20Transmission%20Technologies%20Report%20-%20final%20as%20of%2012.3%20-%20FOR%20PUBLIC_0.pdf

Dynamic Line Rating

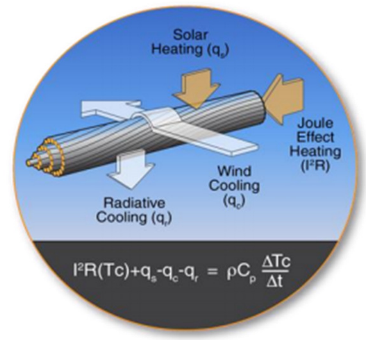

Figure 7. Thermal limits of a line.
Source: Adapted from "Dynamic Line Rating" (DOE, 2019)

Transmission lines cannot carry an infinite amount of power. Thermal and other physical limits exist to prevent equipment malfunction and breakdown from an excessive amount of carried current. The thermal limit of a transmission line determines the maximum current carrying capacity, and the true limit depends on factors like initial line temperature, conductor type, heating from the sun, the cooling effect of wind, ambient temperature, and ground clearance. Because the precise thermal limit of a line cannot be known at all times, estimates are made using various assumptions for each of these variables. There are several types of line ratings that grid operators use to determine how much power can be transmitted across a given line, ranging from simple approximations to complex calculations, that use at least some real-time data to improve the accuracy of assumptions about the line and its conditions [11].

Different types of ratings can be thought of in a few "stages," from least dynamic to most dynamic. Stage 1 contains Static Line Rating (SLR) and Seasonal Line Rating: SLR is the method used to calculate thermal ratings utilizing the most conservative assumptions about the transmission-line's worst-case operating environment, while seasonal ratings are the most common type of ratings, using a different set of static ratings across two six-month periods through the year, each with a worst-case static rating for that time period. Stage 2 contains Ambient-Adjusted Ratings (AARs), which utilize ambient air temperature data that change ratings on a more frequent basis (i.e., daily, hourly, etc.). Finally, Stage 3 contains Dynamic Line Rating (DLR), the most variable of all these rating methods and the focus of this section. Figure 7 summarizes the different types of line ratings and "stages" [12].

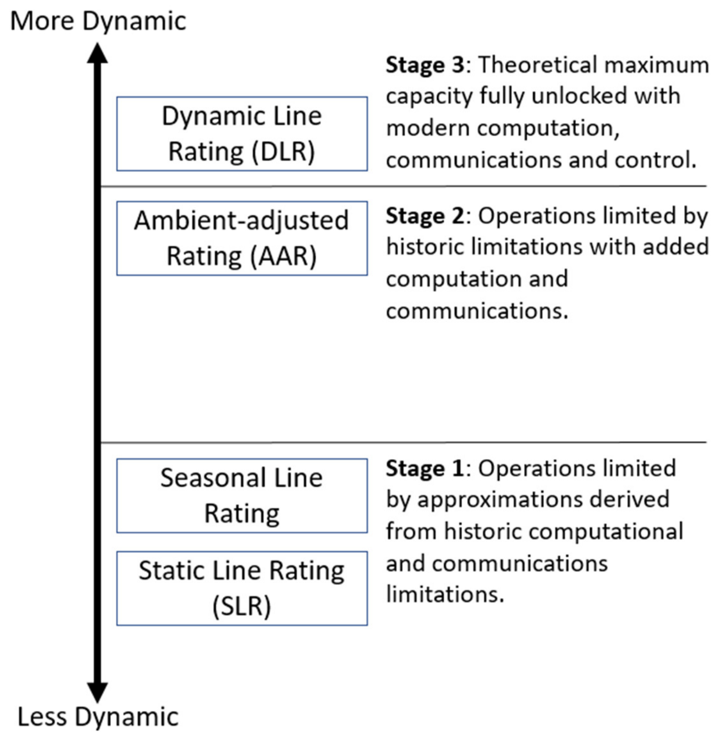

Figure 8. Types of line ratings.

Source: U.S. Department of Energy, Office of Electricity

Current State of Technology

DLR is the term used for a variety of technologies and methodologies that determine conductor thermal ratings (and thus, line ampacity) in a dynamic fashion using granular or real-time data such as weather conditions, wind speed and direction, ambient temperatures, and solar irradiance. Appendix C: Dynamic Line Rating displays an image showing how these factors contribute in different ways to yield one thermal line rating.

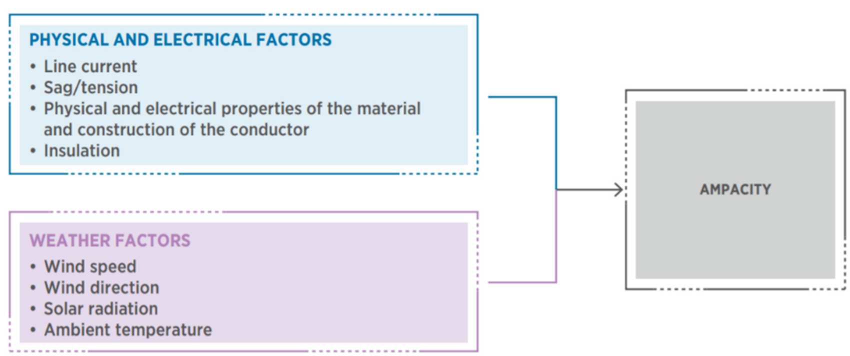

Figure 9. Factors determining ampacity.

Source: Adapted from "Dynamic Line Rating Innovation Landscape Brief," (International Renewable Energy Agency, 2020)

Generally, as seen in Figure 10, a DLR system includes:

1. Sensors mounted on or near the transmission line to be observed
2. A communication system that relays information from field sensors to the control room.
3. A DLR analytics engine for processing and validating the weather and line condition data into usable line ratings for a specified time period.

4. Interfaces with energy management systems (EMS), supervisory control and data acquisition (SCADA) systems, and operators to inform decisions.

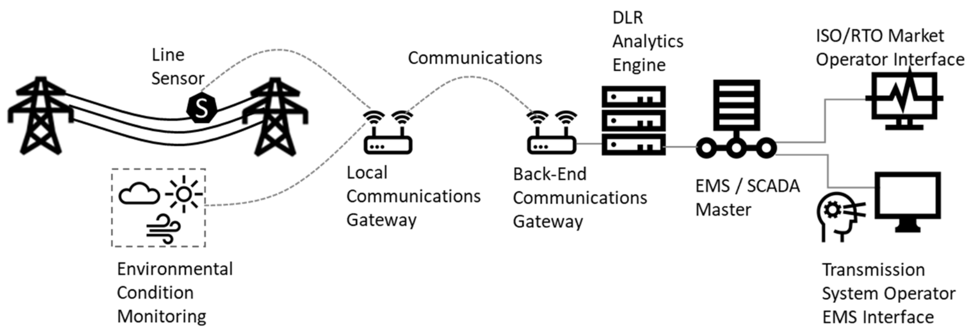

Figure 10. Conceptual DLR system.
Source: Adapted from "Advanced Transmission Technologies" (DOE, 2020)

In DLR systems, sensors monitor, measure, and transmit data that determine the maximum current-carrying capacity of the line in near real-time. There are two primary approaches to DLR systems: (1) monitoring either the conductor directly by measuring parameters like sag, tension, and clearance – direct conductor monitoring – or (2) analyzing environmental parameter data that affects line ratings such as ambient temperature and wind speed/direction – environmental parameter monitoring. Direct conductor monitoring typically results in better accuracy and precision than environmental monitoring alone but requires many costly sensors to be installed on the transmission line to support adequate coverage. There are a variety of technologies used for both direct and environmental parameter monitoring, and the table in Appendix C: Dynamic Line Rating lists some of the common sensors and methods used for DLR, including advantages and disadvantages.

Successful DLR implementation requires more than line data. Rapidly communicating the data to control rooms or decision-makers is essential, especially as real-time conditions may change frequently and suddenly. Several technologies may be used to transmit data, including radio, cellular networks, satellite, and fiber optics; while there are many options for data transmission, cybersecurity remains a priority and concern, especially as grid security is a key characteristic of grid modernization. Once the data are communicated, they must be analyzed and integrated. Raw data can be translated into line capacity using specialized models and algorithms, which can be extremely complex for highly dynamic ratings and add to the difficulty of verifying the accuracy of specific ratings. Finally, once collected, transmitted, and processed, the challenges associated with DLR integration and implementation in a control room are great. Making DLR data accessible and actionable for grid operators is challenging due to the complex and often difficult-to-verify data. Successful DLR implementation requires several innovative solutions across multiple domains.

Across the United States, line rating adoption differs widely across different Independent System Operators (ISOs)/ Regional Transmission Organizations (RTOs) as summarized in Figure 11. Most use a rating more advanced than SLR but less than DLR, such as seasonal ratings and AARs, although a few regions are gradually transitioning to allowing DLR. In some cases, despite the potential benefits, the switch to DLR may be costly for these entities, and the technological investment and operator learning curve to utilize the dynamic ratings is high [11].

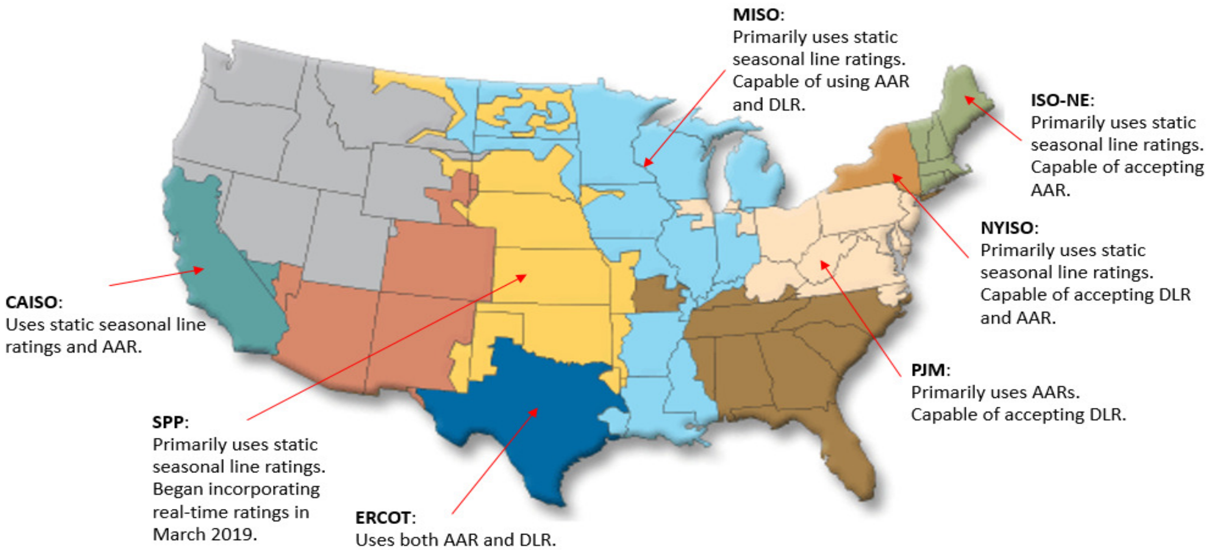

Figure 11. ISO/RTO line rating adoption.

Source: Adapted from "Advanced Transmission Technologies" (DOE, 2020)

There is also a "causality dilemma" with DLR adoption among transmission owners and ISOs/RTOs, as often ISOs/RTOs have no reason to modify existing practices to utilize DLR unless transmission owners adopt it, while transmission owners have no reason to adopt DLR unless ISOs/RTOs can make use of it [13]. Thus, sometimes regulatory bodies must propose rulings or standards to encourage advanced technologies. In November 2020, the Federal Energy Regulatory Commission (FERC) proposed in a Notice of Proposed Rulemaking (RM20-16-000) to require all transmission providers to use hourly AARs for certain shorter-term transmission service. It also required the use of 3-month seasonal line ratings for certain longer-term transmission service, and that all RTOs/ISOs can accept hourly DLR from transmission owners that voluntarily adopt such DLR [14].

Future State and Opportunities

DLR technologies have the potential to provide tremendous benefits to the future electric network. Current areas of research include enhanced data and SCADA integration, longer-term forecast adequacy of ampacity, and the integration of specialized innovative sensors [15]. The future grid, with DLR widely deployed, can expect to see substantial transmission improvements with several meaningful benefits.

Congestion Benefits and Cost Savings. DLR can provide significant opportunities for congestion relief by capably forecasting the expected transmission capacity more accurately, hence a more favorable commitment of generators in day-ahead markets and more efficient dispatch within real-time markets will be possible, thus reducing congestion costs. Figure 12 illustrates a curve of the generic MVA potential from dynamic ratings over static ones, showing moderate congestion relief (due to vastly increased capacity) most of the time [16]. The significant capacity increases, sometimes greater than a 100% than that of a static rating, come from cloudy, windy days, when solar irradiance is low and cooling from wind is high. This leads to a natural relationship between DLR and wind generation sources: high wind yields (a) more wind power, and (b) cooler transmission lines that, when DLR is used, can transport more power from those wind resources [17].

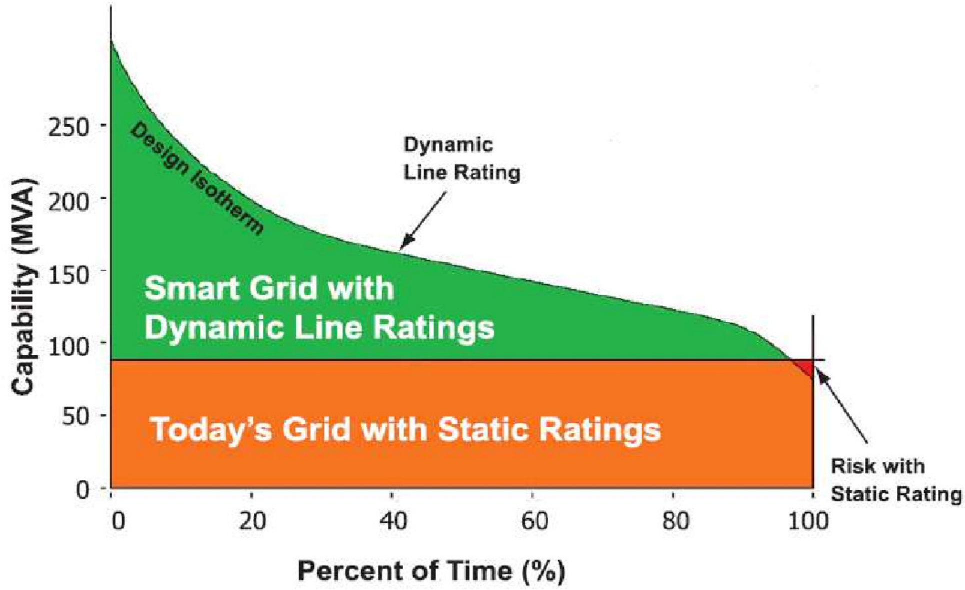

Figure 12. Capacity potential from DLR versus SLR.
Source: Adapted from "Dynamic Line Rating Oncor Electric Delivery Smart Grid Program," (J. Johnson et. al., 2013) [18]

It is widely accepted that the implementation of DLR can provide congestion-management benefits, a conclusion demonstrated in several studies. A 2018 PJM study found that the use of DLR equipment on one line could save the RTO $4 million over one year [19], and a 2019 FERC staff paper on line ratings discussed the Potomac Economics finding that the utilization of AARs could have saved "$165 million in 2015, $155 million in 2016, and $127 million in 2017" in congestion costs for the MISO region [20]. The benefits to congestion and the cost savings potential from DLR technologies are evident and substantial.

As the grid changes and the growth of variable renewable generation such as wind and solar increase, greater uncertainty and intermittency highlights the importance of DLR in congestion management.

Improved Situational Awareness. DLR systems are also an important tool in improving situational awareness for utilities. The same sensors that DLR systems require can also be used for asset health monitoring, informing transmission owners of line health and approximate remaining lifetime by processing line conditions. For example, the situations and impacts of icy conditions or nearby wildfires could be better and more quickly understood with DLR sensors. Another specific use case of these sensors is seen in the "Risk from Static Line Rating" segment of Figure 12, when DLR can detect actual line ratings lower than ratings calculated from static methods. When this does occur, such as during a very hot day with high solar exposure and no wind, DLR can assist system operators in mitigating risks by identifying lines loaded beyond real-time capability. DLR can also provide the data to assist in wildfire prevention strategies, including methods to operate the grid and timing on clearing vegetation or upgrading equipment, therefore not only improving situational awareness but also enhancing safety [11].

Accelerating Grid Modernization. DLR has the potential to notably advance several aspects of grid modernization on the transmission system. DLR allows for enhanced flexibility during extreme events and provides additional tools for grid operator. For example, during extreme cold weather that causes equipment malfunction and outages, operators can utilize colder temperatures to direct more power through certain lines and mitigate or eliminate the negative effects from the event. This solution increases reliability and resilience for grid infrastructure. Further, the data from DLR can be used over a longer period of time to gain insight into a line's performance, which boosts reliability through identification of at-risk power lines (such as which lines are most prone to cause wildfire-causing sparks), for example. Resilience, reliability, and flexibility are all greatly strengthened with the widespread deployment of DLR technologies [11].

Challenges

Despite DLR technology's potential to reduce congestion and increase grid flexibility, reliability and resilience, there are several challenges and limitations preventing its widespread adoption, including the concern over its implementation costs, data accuracy and reliability, and current lack of operational knowledge. Widespread implementation of DLR will require solving or mitigating these challenges.

Economic Hurdles. Although the implementation costs for DLR technologies are not as high as those for significant infrastructure installation, utility and transmission owners have often been reluctant to adopt DLR technologies due to several factors. For transmission owners, insufficient incentives limit the attractiveness of DLR technologies, and optimal utilization of DLR may not always be attractive as constantly operating a line at its limit may reduce its potential lifetime as compared with a line run with significant headroom [11]. Further, investment classification and market structures add hesitancy to technology adoption which in some cases, due to return on equity (ROE) categorization, may cause owners to favor traditional transmission buildout. In April 2021, FERC announced a September 2021 workshop "to discuss certain performance-based ratemaking approaches, particularly shared savings, that may foster deployment of transmission technologies," examining these economic hurdles that limit deployment of technologies like DLR [21].

One more economic factor for DLR is that even as studies have clearly demonstrated the benefit of DLR technology, there are few studies performed comparing the relative effectiveness of AARs vs. DLRs; some may opt for a simpler, less costly rating with AAR if it still maintains a high percent of the cost-effectiveness as DLR. Finally, the high costs associated with the installation, maintenance, and protection of DLR sensors may lead to more implementation hesitancy [13].

Inaccurate Data. DLR technologies generally produce accurate data, but inaccuracies can occur due to either measurement or modeling errors which may reduce operator confidence and trust in what they are making decisions from. The accuracy and reliability of DLR is critical for greater industry acceptance and implementation; developing methodologies and solutions to address these concerns will be critical to broader DLR adoption. Some strategies currently under investigation have employed a mathematically described confidence level within the DLR calculation, which rates transmission lines more or less conservatively proportional to parameters of different confidence levels such as temperature or forecasts [13].

Required Operational Knowledge. The transition from SLR to DLR requires buy-in and time for operators to adapt, implementation of new control room software or hardware, and additional employee training. Those factors might impose risks to DLR implementation causing reluctance in its adoption. DLR integration is one of the most challenging steps in implementing DLR systems due to the addition of one more complex system to busy control room operators [13]. One other specific factor that has been reported to hinder DLR implementation is the common misconception by operators that DLRs would result in control rooms having line ratings that move around unexpectedly in real time in a way that would be harmful to operations and reliability. In reality, while DLRs (and AARs) are often nominally described as "real-time" ratings, DLR and AAR methodologies produce ratings that are fixed over the time period to which they apply and that do not change unexpectedly. In other words, DLRs are close to real-time (particularly when compared to SLRs or seasonal line ratings), and are more accurately characterized as "hour ahead" (or other applicable interval) rather than "instantaneous." Improved operator familiarity with DLR implementations may help overcome this misconception and thus this hinderance to DLR implementation.

Limits of DLR Technology. Dynamic Line Rating maximizes the thermal limit of a line. However, as power flows from generator to end user, it must also pass through substation equipment. Components within a substation – including transformers, switches, circuit breakers, and relays – all have their own current-carrying capacity limits, and may be the limiting elements on some circuits, which would prevent conductor DLRs from providing benefits there. Also, while DLR in parts may reduce congestion in some areas, it may in effect shift the congestion elsewhere, to a part of a system using a less dynamic method [11].

The challenges facing DLR implementation in the U.S has led to other countries adopting advanced transmission technologies at a faster rate. Furthermore, more pilot studies and demonstrations that can show capacity increases are an important tool for industry adoption of DLR. Numerous electric network stakeholders have expressed support for DLR, but technical, market, and regulatory challenges remain that must be addressed to facilitate broader adoption.

Topology Optimization

The electric grid is a highly complex network of lines and nodes, with a nearly limitless number of ways to configure the grid to transfer power across the network from point A to point B. While the grid has historically been considered a "fixed" asset whose lines all must be kept in service, research and some experience has shown that some grid configurations which involve switching some lines out of service result in power flows that are less expensive and more reliable than others. There are some methods that switch lines in and out of service to optimize power flow across small or large segments of the grid. Optimizing one part of the grid, even over just a small number of switches, can potentially result in a more efficient system, and has been shown to have great cost savings potential [22].

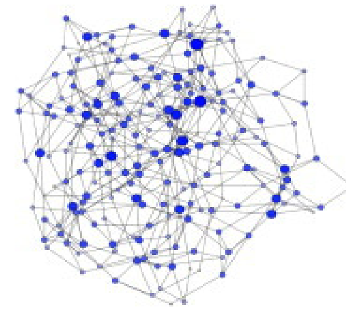

Figure 13. Example Topology Network.
Source: Adapted from "Power Grid Network Evolutions for Local Energy Trading," (Pagani, G.A., Aiello, M., 2012)

The decision of how to configure the power system becomes difficult when the number of lines and generators are in the thousands or tens of thousands. Optimizing at this scale becomes a highly difficult mathematical problem and thus requires advanced computing and system-level methods [23]. Topology Optimization is a systems-level approach that enables power flow routing on the grid, generally implemented as a mathematical method that optimizes a system's layout. It can be defined as the structured method of optimizing the electric grid system's layout within a given boundary, for a given set of existing and future (planned) loads and constraints with the goal of maximizing the performance of the system. While DLR eases the load on individual lines, topology optimization and the related application of applied controls to the installed topology refers to a broader set of technologies used to control, route, or segment a transmission line to minimize congestion. It may also be used to eliminate voltage violations during lightly loaded hours [13].

A "topology" in reference to the grid refers to how it is connected: there are many possible grid topologies, each with their benefits and shortcomings. Much like DLR, advanced grid equipment or advancements may be needed to enable the requisite sensing and control to dynamically (re)configure and optimize the system or protect it from faults, outages, and other anomalies.

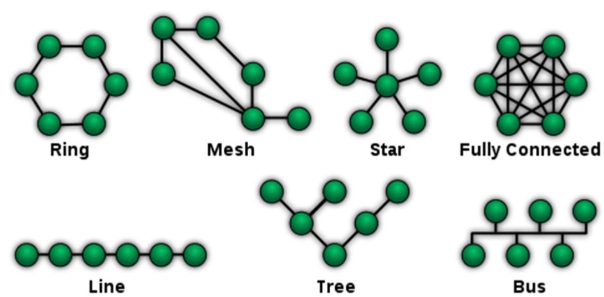

Figure 14. Different network topologies.
Source: Public domain

Advanced optimization methods, some developed by the U.S. Department of Energy (DOE) and the National Laboratories, will aid in modernizing the grid and may increase the hosting capacity of the grid for new energy-efficient and renewable technologies. The remainder of this section will explore these concepts of topology optimization, its relationship to controls, and the benefits of topology optimization to provide clear utility benefits. These benefits include extending operational lifetime of installed infrastructure, alleviating grid modernization costs, and improving the carrying or hosting capacity of DER including photovoltaic (PV) power, wind power, electric vehicle supply equipment (EVSE), etc.

Current State of Technology

Topology optimization includes a structured method of controlling or utilizing the electric grid system's layout to stay within needed system constraints. For example, it is possible to rudimentarily remove or disconnect a line from service temporarily under certain conditions to improve overall system efficiency while not jeopardizing the reliability of the larger system. Power system engineers have developed advanced techniques, methods, and preferences to both evaluate and optimize the grid's topology to improve operations – one such example is leveraging a "digital twin" model, a computer model "twin" of the physical infrastructure for evaluations, studies, and reconfigurations [24]. The software tools for topology optimization, especially on a small scale, currently do exist, and often are impeded in practice by other factors.

Currently deployed topology control methods are based on legacy topologies, limited sensing, and rudimentary control. For example, system operator expertise is used in a manual process to identify switching candidates ahead of events. These switching decisions are typically based on historical, documented switching actions that were evaluated under previous events or that were determined not to result in unintended consequences. Either way, the lack of rigorous analysis may result in overlooked opportunities for improvement [13].

Ultimately, just as the placement, siting, and interconnection of new technologies into the electric grid infrastructure is an integration challenge, so too is the management, optimization and control of the electric grid through dynamic line rating, power flow manipulation, and asset control given the grid's topology and "levers" available to optimize it. DOE's Transformer Resilience and Advance Components (TRAC) program is one DOE program that manages the basic building blocks that unlock the capability of the grid to be integrated and managed as an optimized system [25]. The basic building blocks coupled with (enhanced) system sensing and control, lead utilities – like the Electric Power Board of Chattanooga – to dynamically manage their system as networks of microgrids or, abstractly, reconfigurable nodes within a grid topology that supports better system management, improved reliability, and added resilience [26].

Future State and Opportunities

Any use of topology optimization in U.S. energy markets, even on a small-scale, would represent an innovation compared to the current state of technology. Small-scale optimization is not computationally difficult and is often feasible for use in a system, but implementation is limited by other factors. At any scale, topology optimization has significant potential to increase the system's capacity and utilization.

Specific technologies, including data-driven analysis, real-time analytics, machine learning, and artificial intelligence can be leveraged to enable topology optimization to address transmission challenges through identification of optimal controls and power flow. Advanced software[d] or "digital twin" models can provide the system's current state, evaluate switching options, and present possible control actions to operators. These capabilities assist with reducing costs, mitigating abnormal conditions, improving reliability, or better positioning the system as a resilience measure [27].

There are several primary use cases where topology optimization has the potential to significantly improve a technical or operational aspect of the grid. Because topological optimization can dynamically change, modify, and restructure power flows across a wide area, these use cases typically address and accrue value to multiple entitles or aspects of the utility's business model.

Improving Operational Challenges. Any integration of topology optimization can improve grid operations and reduce congestion. A 2018 study by SPP, shown in Figure 15, applied topology optimization to a small portion of their region in the Midwest to reduce wind generation curtailment, lower costs, and improve contingencies [28]. This study is one of many that illustrates the potential for widespread topology optimization. Other studies include a PJM study identifying a 50 percent reduction in real-time congestion costs – equivalent to annual savings over $100 million – and a study performed in the United Kingdom concluding that enhanced topology optimization could save approximately $50 million per year. Topology optimization will assist operations, reduce congestion, and minimize curtailment.

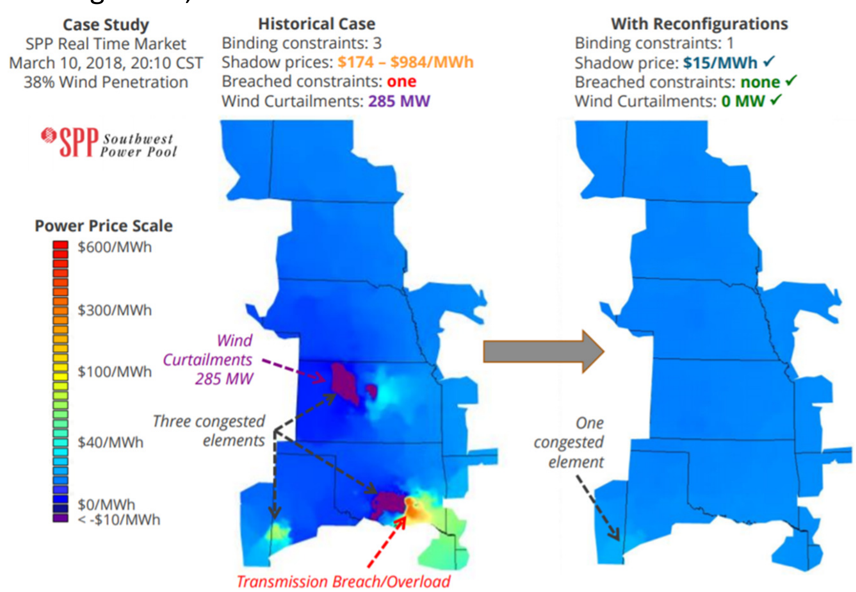

Figure 15. SPP study detailing congestion and curtailment relief using topology optimization.
Source: Adapted from "Transmission Topology Optimization," (P. A. Ruiz, D. Bowman, K. Dial, X. Li, R. Schoppe, Z. Sharp and B. Tsuchida, 2018)

Improving Planning Challenges. As the electric grid of today transforms, topology optimization provides a powerful tool for system-level planning. The tool can be used to reduce or eliminate violations, minimize outages, and strengthen reliability in the evolving system. In some instances,

[d] More information on available topology optimization software can be found in DOE 2020, Advanced Transmission Technologies, Report. December 2020. Section VII. Appendix – Topology Optimization.

system planners may be able to rely on topology optimization schemes and capabilities to accommodate disasters or unpredictable events, by planning to adjust topology in real-time to maintain system performance while not incurring costs or violating constraints (e.g., N-1 contingent) [13].

Improving Economic Challenges. While the economic value of topology optimization is apparent in its saved costs through congestion reduction, the application of such methods may also result in transmission investment deferral. By maximizing the utilization of existing lines, the financial need for new, costly installations may be lessened or eliminated, resulting in delayed or cancelled upgrades. Furthermore, once these infrastructure improvements are implemented, topology optimization will maximize their utilization too, refining all lines and reducing the need for excess line installation. Because this is a solution that does not require significant investment on its own, topology optimization offers an inexpensive option to maximize utilization of the current, and future, system [13].

Accelerating Grid Modernization. Through the integration of these use cases, characteristics of grid modernization are strengthened. Reliability and flexibility come from the improved operational challenges, while reliability and resilience benefits are felt from improved planning topology optimization provides. The application of topology optimization lends itself to a more efficient, flexible system that can support a variety of future needs. As the system continues to evolve and the architectures of different regions may diverge, the principles of topology optimization will enable the transition and support the many possible futures of the grid.

Challenges

Barriers persist that reduce the widespread usage of Topology Optimization as an operating standard for the industry, and each represents an opportunity for new solutions to solve problems and become attractive businesses for utilities to consider. Following are the barriers of topology optimization, first outlined in DOE's 2020 *Advanced Transmission Technologies* Report.

Model Size. The U.S. power system is enormous and complex. It is likely that the first instance of applied topology optimization will be on modeling and simulating small systems (transmission branches or segments), but future instances will handle exponentially increased complexity with a larger model size. It is extremely difficult to capture all aspects of the grid as a whole and perform optimization on the entire topology, and models that do may require extensive time or resources to run. For example, high-performance computing (HPC) application may reduce computation time, but it is also much more costly. More efficient algorithms and models are an active area of research but attempting large-scale topology optimization will yield a complex, difficult-to-solve model.

Data Accuracy. To run a model as large as the electric grid reasonably and in a finite amount of time, approximations or simplifications must be made. However, simplifying model parameters significantly risks the accuracy of the data, and confidently deciding which simplifications can be made is often difficult. Without algorithms that operators can be confident will give them accurate results rapidly, topology optimization has a far more limited opportunity for widespread application. More development of algorithms and solutions to balance model size, speed, and accuracy will enable further use of topology optimization.

Direct Impacts on Physical Infrastructure. A fully optimized system places more strain on hardware components, such as circuit breakers, by maximizing their utilization. This may accelerate the aging of hardware and result in more malfunctions, increasing maintenance costs and impacting component (and system) reliability.

Indirect Impacts on Physical Infrastructure. Topology optimization utilizes switching operations to change between different system architectures. However, this switching is associated with grid disturbances that may impact stability. There are technical solutions to this problem, such as added tools to confirm system stability under different topology reconfigurations, but this remains an important consideration for implementation [13].

R&D Opportunities

DLR and topology optimization can be applied concurrently as solutions to optimize the utilization of the current electricity delivery system, reduce the frequency and duration of outages, and generally improve the reliability of the system. The coupling of DLR and topology optimization, enabled through power flow controller, node segmentation, or other control technologies, can improve system efficiency and operating performance while decreasing modernization and upgrade costs. These technologies, controlled together or utilized independently, will benefit the system as its variability increases and optimal responses to unpredictable events are needed. DLR and topology optimization advancements, or *network optimization*, will be critical for solving the grid's future challenges, but more R&D is needed to develop fully realized technology solutions in this area.

There are three primary research needs to be highlighted for network optimization. The R&D areas listed are generally for the near-term, as network optimization technologies are fairly mature and require some specific R&D actions for further pilots and wider deployment.

R&D Area 1: Enhanced Models and Data. To implement software-based optimization solutions into the grid, advancements to the tools themselves are needed. Efforts and capabilities within the Department of Energy, like ARPA-E's Grid Optimization (GO) Challenge, the Advanced Manufacturing Office's HPC4MFG program's supercomputing facilities, and the Office of Electricity's Advanced Grid Modeling (AGM) program, are aiming to advance grid models and data accuracy to fully realize the potential of network optimization. Within both topology optimization and DLR advancements, lack of confidence in models limits deployments, and more research is needed to ensure the accuracy, speed, and low cost of collected and analyzed system data. Specific areas of research include transmission switching methods for topology optimization implementation, high-fidelity sensors, and advanced algorithms. Also needed are software solutions to enable secure, standardized, and robust implementation of DLR and topology optimization into existing EMS or SCADA infrastructure.

16 illustrates the R&D for topology optimization models, synthesizing model-driven solutions with data-driven solutions to yield system-level results.

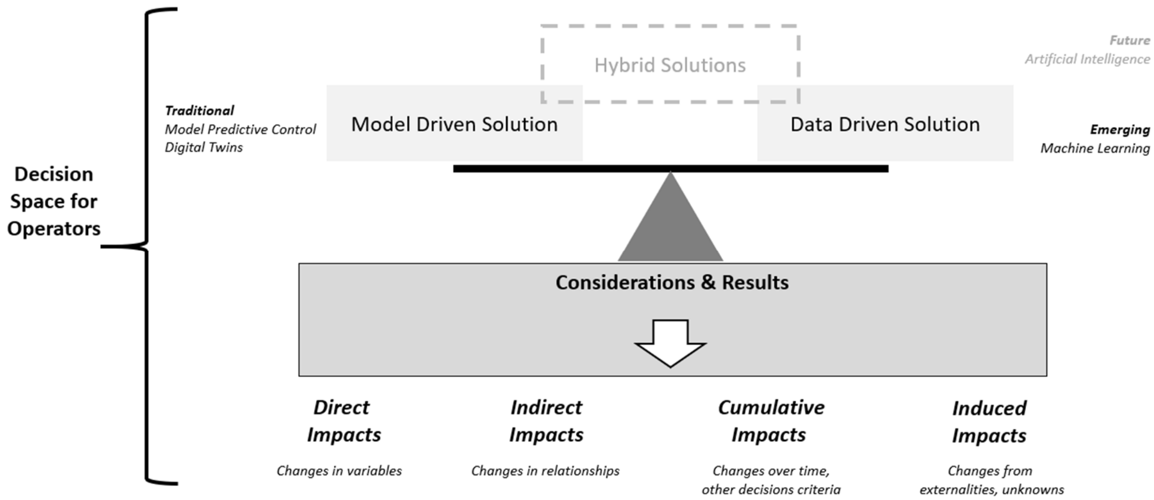

Figure 16. Summary of R&D for topology optimization.
Source: U.S. Department of Energy, Office of Electricity

R&D Area 2: Evaluation of Impacts. For utilities and transmission owners to consider implementing these advanced optimization techniques, further evaluation is needed in determining the system impacts of such technologies. For those who have implemented DLR or topology optimization, close monitoring of the system impact (in a deployment study) is critical. Both the advantages – congestion relief, annual cost savings, infrastructure deferral savings – and the disadvantages – increased aging of hardware, operational complexities, data accuracy – must be evaluated for a full understanding of the impact these technologies have on the entire system.

Another approach is to evaluate the impacts through case studies. Although it is often difficult to extrapolate results beyond one case study due to the specific or complex nature of some assumptions for a given region, studies still help demonstrate the benefit of optimization technologies and build stakeholder confidence. While there are some studies that relate DLR and topology optimization to congestion relief and other cost benefits, there is little study data about other longer-term impacts such as the extent to which increased system utilization may age critical hardware and impact its maintenance and replacement. Also, more research on real-time line conditions is needed to determine the practical impact of such technologies, although studies on real-time conditions are also costly and difficult to implement. Increased utility confidence in these technologies will rely on further impact studies and evaluations of all aspects of system integration.

R&D Area 3: Workforce Development and Technical Assistance. Once the technology is further developed and utilities implement these advanced solutions, a developed workforce is needed to ease deployment of sophisticated modeling techniques and advanced digital technologies. Grid operators must already manage many factors, which will only increase with greater network complexity, so additional input (such as what is provided from DLR) may be unwelcomed. Thus, developing a pipeline of power sector operators equipped for these modernized, advanced technologies is essential. Robust technical assistance and continuing education for policymakers, regulators, and utilities given on planning methods, architecture design, and optimization will aid in the implementation of these technologies, while investments in programs aimed at university and K-12 students will ensure the rising workforce is well-equipped for these technologies. Specifically, private/ partner partnerships for more pilot programs may help utilities gain more expertise in implementing advance technologies. Prioritizing this area will ensure a diverse, dynamic, and capable workforce for utilizing optimization and advanced methods in the modernized grid [29].

The challenges facing both DLR and topology optimization implementation can all be mitigated or solved through one or more of the listed R&D areas. Figure 17 summarizes how these technologies match to each R&D area, and demonstrates the actionable R&D areas that can be prioritized for higher penetration of these technologies on the real-world system.

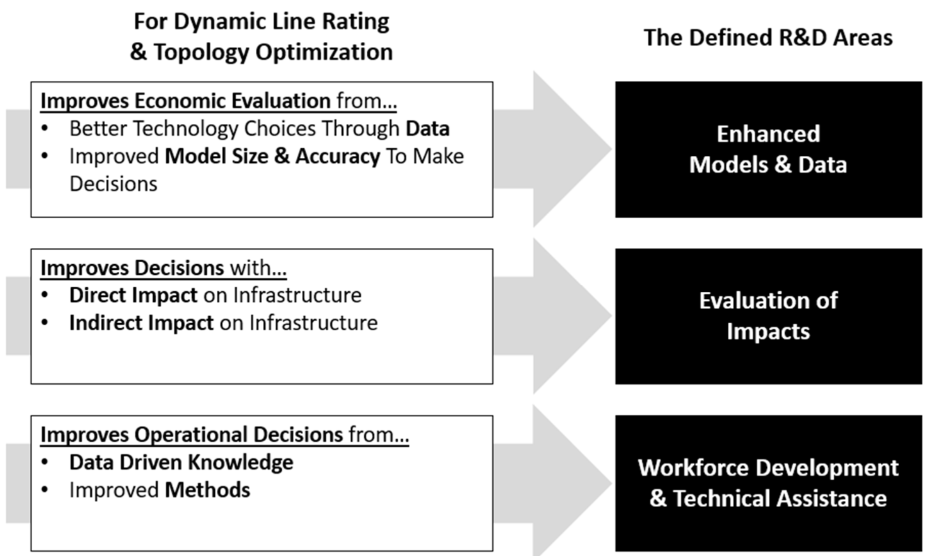

Figure 17. Summary of R&D for DLR & topology optimization.
Source: U.S. Department of Energy, Office of Electricity

III. Power Electronics in the Future Grid

As the grid of today undergoes its transformation to the future network featuring DER, dynamic customer demands, and low-inertial renewable resources, hardware devices will play a key role. Without basic hardware infrastructure, the grid could not function, but emerging technologies in the field of Power Electronics (PE) offer the opportunity to impart significant flexibility and response speed attributes when employed with proper planning and design. “Power Electronics” describes a set of technologies that focus on the transformation and management of electrical power and is applied in almost all modern electrical devices, from small devices to critical grid junctions [30].

One of the key goals of PE system development is to standardize the interfaces between different technologies and applications and provide significant improvements in grid modernization metrics: reliability, resiliency, power quality, security, affordability, and efficiency. Adoption of these PE building blocks for different grid applications and realizing a coordinated control architecture can provide the following significant benefits:

- Reduce operation & maintenance (O&M) costs and balance-of-system (BOS) costs through standardization of interfaces and interconnects.
- Allow for higher DER penetration by localizing generation and consumption without the need for capacity expansion or costly system upgrades.
- Enable new grid architectures/ paradigms, such as DC distribution, and accommodate loads and sources required in the future.
- Provide flexibility and increased response times through features such as autonomous response.
- Promote modular, scalable, interoperable, and cyber-secure systems at a lower cost through standardized and secure PE building blocks.
- Enable functions like black start and other capabilities to mitigate the impact of catastrophic grid events.

Increased penetration of power electronics in the grid is happening through development of high-power drives (like in Type-3 or 4 wind turbines, industrial variable frequency drives, etc.), high-voltage direct current (HVDC) systems, Flexible AC transmission system (FACTS), energy storage systems (ESSs), inverter-based renewables like solar and wind, EV chargers, and other technologies. Ongoing research and development in new power electronic technologies including, but not limited to, solid-state power substations (SSPS), extreme fast charging (XFC), solid-state transformers, and multi-port power electronics that integrate multiple sources/loads will further increase penetration levels. These technologies represent a range of benefits on future grid architectures, but each has its own implementation challenges [31].

In this section, two specific R&D areas relevant for power electronics applications will be discussed: power flow controllers – for both alternating current (AC) and direct current (DC) – and solid state power substation (SSPS).

Power Flow Technologies

As DLR and topology optimization “unlock” capacity within the electric system through software or analytics, specific hardware devices are used to address the thermal, voltage, and stability constraints themselves. These devices may come in the form of added grid infrastructure, and thus may be more expensive than the devices or tools used for optimization methods, but may increase long-term reliability through changing the fundamental properties and variables that enable the grid to function. Some of these devices date back decades to the start of the grid, and more recent advancements deploy power electronics in power flow technologies to develop a smart, resilient grid.

Current State of Technology

There are two families of power flow devices, representing the two operating modes of electricity systems: Alternating Current (AC) and Direct Current (DC). Most of the electric grid in the U.S. is operated in AC, and there are many different devices that can benefit the characteristics of such a system. Mathematically, there are four physical properties of the system that determine how real power (P) and reactive power (Q) flow from one end of a line to the other for AC [32]:

- V_S, the sending end voltage
- V_R, the receiving end voltage
- X, the reactance of the line
- δ, the difference in phase angles between the sending and receiving end voltages

The relationships between these variables apply to any one transmission line in the system where power flows from one point to another. Power flow controllers (PFCs) exist that manipulate all four of these values to allow the maximum amount of electricity possible through the system. Generally, changes to voltage have a greater effect on reactive power flow, while changes to line reactance have a greater effect on real power flow. Conventional PFC technologies include phase-shifting transformers to control phase angle, series capacitors to control impedance, and switched shunt capacitors and synchronous condensers to control voltage. More information on these technologies and deployments can be found in the Appendix of DOE's 2020 *Advanced Transmission Technologies* report [13].

DC power flow controllers, while not able to modify the variables of an AC power flow directly, have use within their own DC systems. High-Voltage Direct Current (HVDC) systems can transport large amounts of power within and among asynchronous AC systems, providing a service not possible with any other controller or grid-enhancing technology. In North America, there are several HVDC lines and interties in operation, supported in part by reduced cost of power electronics components. Figure 18 displays the HVDC links of North America [13].

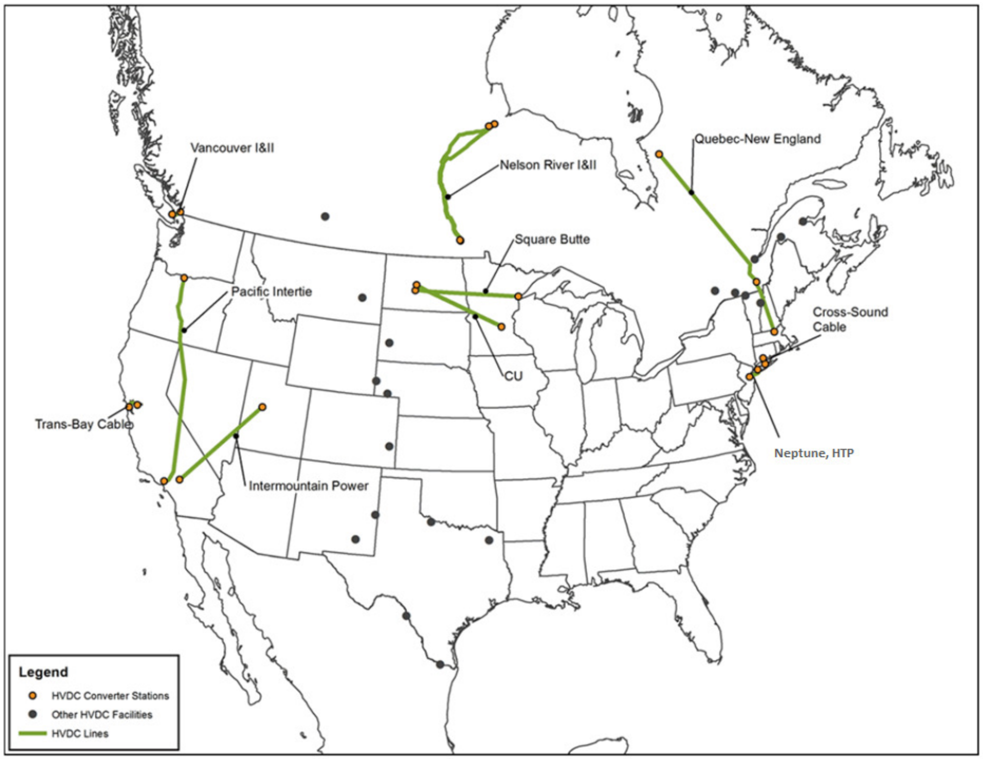

Figure 18. HVDC links of North America.
Source: Adapted from "Advanced Transmission Technologies," (DOE, 2020)

Multi-Terminal DC (MTDC) are DC lines that have multiple points of connection to load centers or generators. Such systems benefit from the same advantages as HVDC systems, and can also be more economic and flexible than single HVDC lines. Though such system topologies are complex, the capability of MTDC to optimally integrate large-scale offshore wind is a unique benefit and makes the technology an active area of research even though there are only a few active MTDC deployments worldwide [33].

Future State and Opportunities

While there are many traditional power flow devices that are fundamental to grid operations, there is a rapidly emerging field of more dynamic hardware, utilizing power electronics, that have the potential to enable the electric grid transformation that other technologies – like DLR and topology optimization – are also enabling.

Both advanced AC and DC power flow devices promise significant benefit for the transforming electric network. The previous section outlined several conventional AC devices, but there are others that incorporate solid-state components, like FACTS, that are emerging as a viable contender to control power in the future network. FACTS devices for controlling impedance include thyristor-switched compensators and static synchronous compensators (STATCOM), for voltage include static var compensators and static compensators, and for other control applications include unified power flow controller (UPFC) and interline power flow controllers (IPFC). These devices, alongside advanced HVDC solutions, have the potential to support sustained reliability and controllability through the trends and challenges today's grid faces [13].

Congestion Relief. Much like DLR and topology optimization, PFCs have the capability to alleviate congestion. For AC, active control of system parameters yields greater flexibility and efficiency than passive control. A 2018 study performed by EPRI found that one power flow device implemented in the PJM region had an annual cost savings of $39 million from reduced congestion, while 17 devices saved $196 million. However, the addition of the first several devices had a much greater impact than the addition of the last few, as shown in Figure 19 [34].

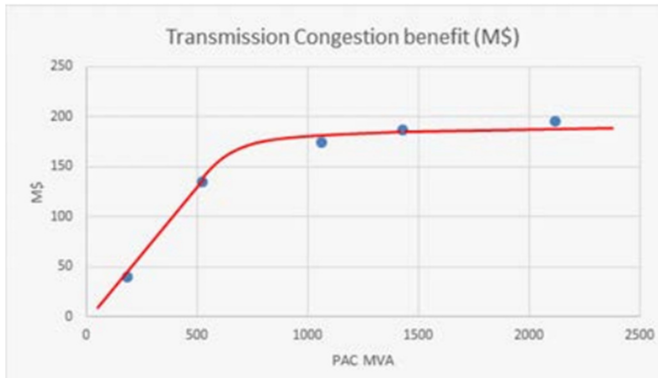

Figure 19. Summary of R&D for DLR & topology optimization.

Source: Adapted from "Benefits and Value of New Power Flow Controllers" (A. Del Rosso; E. Ela; S. Uppalapatti; J. Roark; A. Tuohy; L. Trinh; J. Zhui, 2018)

HVDC technologies have their own congestion benefits. HVDC links may bypass areas of high congestion within AC systems, directly connecting two points that would otherwise contain congestion between them. Furthermore, because of the physics of AC vs. DC power flow, the transmission capacity of an HVDC line is 40 percent higher than an AC line at the same voltage rating. Also, the losses on HVDC lines are almost 50 percent less than the losses on AC: 3.5 percent per 1,000 km vs. 6.7 percent per 1,000 km. Over a long distance, these factors highlight HVDC as an effective tool to reduce congestion [13].

Transmission Expansion Flexibility & Deferral. Through maximizing the utilization of existing infrastructure, PFCs allow for the flexibility and deferral of transmission upgrades. As PFCs can be installed gradually and where needed, such devices can be flexibly deployed, removing the need for costly, extraneous solutions. The same 2018 EPRI study that evaluated the impact of PFCs on congestion also analyzed the cost difference of several transmission projects against alternative PFC solutions. The findings, summarized in Table 3, are clear: PFCs have the potential to provide a more cost-effective solution than transmission buildout, saving millions of dollars in the short-term through deferral [13].

Table 3. Comparison of PFC and Transmission Solution Costs

Source: Adapted from "Advanced Transmission Technologies," (DOE, 2020)

Case	Original Project	Original Project Cost	PFC Alternative	PFC Cost Range	Comments
1	New 115-kV line to remove overload at N-1 condition	$16.8 M	Installation of PFCs on two parallel lines	$1.5 M–$5.2 M	Impedance changes necessary to avoid overload change over time. PFCs can be installed gradually over time.

Case	Original Project	Original Project Cost	PFC Alternative	PFC Cost Range	Comments
2	Reconductoring 115-kV line and upgrading 230/115 kV substation to address overload caused by transformer outage	$7.15 M	Installation of PFC on 115-kV line	$2.4 M	Deferral time greater than 10 years. PFC solution eliminates overload of two system components caused by the same contingency, and can replace the original project.
3	Rebuilding 26 miles of existing 115-kV line	$14.2 M	Installation of PFC on 115-kV line	$2.0 M–$5.0 M	Cumulative value of deferral greater than $2.0M after year two and greater than $5.0 M after year five. PFC can be a cost-effective solution if project can be deferred more than two years.
4	Rebuilding 77 miles of 138-kV transmission corridor to address overload due to outage of 345-kV line	$60.2 M	Installation of PFC on 138-kV line	$2.4 M–$3.7 M	Cumulative value of deferral greater than $4.0 M after first year. PFC can be a cost-effective solution even if deferral time is very short.

Some upgrades cannot be deferred, however. When a line must be built, HVDC technologies sometimes have cost and flexibility benefits, particularly for longer transmission lines[e].

Accelerating Grid Modernization. AC PFCs greatly benefit several areas of grid modernization. PFCs contribute to the flexibility, reliability, and resilience of the system by allowing for rapid, controlled response enabled by power electronics. With increasing renewable penetration in the grid, and the associated lack of system inertia, PFCs are used to provide support on different time scales in order to ensure system reliability. Advanced power flow solutions are needed to successfully incorporate the desired renewable generation, distributed generation, and variable demands into the electric network.

DC technologies have their own specific use cases that enable grid modernization. DC links, with enhanced flexibility to connect asynchronous systems, for example, can act as links for underground, undersea, or worldwide applications. HVDC may also enable new system architectures, like fractal microgrids, and benefits resilience by assisting the grid with black start capabilities.

Challenges

While different types of PFCs promise significant benefits to an evolving grid, there are some barriers that must be overcome to achieve widespread deployment.

System Planning and Regulatory Limitations. Current transmission planning processes may limit the implementation of PFCs, as planners may be unfamiliar with how to properly model their impacts. While there are some devices, like phase shifting transformers, that power system engineers regularly study and install, there are many others that are difficult to implement given current procedures. For example, even as HVDC lines in operation allow industry to study and address operational challenges, more developments of HVDC systems are needed to eliminate

[e] Shorter HVDC lines are generally not economical due to higher terminal costs than AC lines.

adoption barriers. Furthermore, PFCs require the consent of transmission owners to be installed, which adds another challenge to grid integration. There are several regulatory and planning challenges associated with PFCs, a direct result of the immense complexity of grid ownership.

Economic Barriers. PFCs currently suffer from high costs and insufficient evaluation of cost impacts. Also, the current market structures of the grid may act to limit PFC installations, especially in large numbers. This is in part caused by these markets assuming a static transmission infrastructure, the very paradigm that PFCs and topology optimization methods aim to upend. New market mechanisms designed to handle many PFCs, and the flexibility they provide, may be needed, as well as a more active role by market operators to reflect this dynamic shift.

For DC, high converter costs mean that HVDC systems are only cost-effective after a certain distance, which may be over 100 miles for overhead lines (the distance is shorter for subsea DC cables). Complex system components, which are not necessarily interchangeable across different vendors, also add to costs. Furthermore, allocating benefits may be difficult when an HVDC line runs across states that are not receiving the benefits from either end of the HVDC point-to-point transfer; this situation may be mitigated with MTDC systems, though such systems have their own complex implementation challenges [33]. Similarly, the economic impact of HVDC may not be felt as rapidly or reliably as for an AC line, limiting implementation potential.

Implementation Challenges. In general, PFCs have insufficient incentives for implementation, and suffer from market and regulatory challenges. More studies will need to be done on impacts, and some structures will need to be rethought, so that implementation becomes more attractive to the complex set of grid owners. For HVDC, modeling the new dynamics and interactions from dynamic PE devices is challenging, and will also require its own set of impact evaluations and studies. Managing and capturing these types of dynamics and complex system interactions will be critical for decision-makers to incorporate HVDC into the network [13]. Finally, while MTDC systems have potential to improve grid flexibility and implement a greater amount of renewable energy (such as offshore wind), they face implementation challenges including system stability, control and system integration [35]. More R&D is needed to efficiently implement power flow devices into system operations.

Solid State Power Substations

Substations are critical to the management of transmission and distribution networks through voltage transformation, electrical isolation, power flow management, and power system protection [36]. Substations play a vital role in managing power flow and serve as a hub for connecting multiple power lines. They also maintain power quality, regulate voltage, and assist with fault tolerant power delivery.

This section highlights advanced solid-state power substations that incorporate PE converter systems along with other substation equipment for filtering, monitoring, and protection. This technology differs from other PFCs and network optimization tools in that it is less mature; there is a roadmap for SSPS development and deployment, but no deployments of it currently exist in the U.S. or globally. However, the outcomes of the roadmap demonstrate the great potential of power electronics to solve the challenges in the future electric network.

Current State of Technology

At the outset of grid evolution, substations were predominantly categorized based on their location in the system, as a: (a) generation substation, (b) transmission substation, or (c) distribution substation. However, with developments such as the invention of circuit breakers and power semiconductor devices like the insulated gate bipolar transistors (IGBTs), switching substations and converter substations were added as additional options. Appendix D: SSPS contains a table of conventional substations and general purposes, as well as a detailed list of the devices within substations [36].

The evolution of the grid is heavily straining the capabilities of the conventional distribution substations which were designed for one-way power flows in grid dominated by centralized (predominantly fossil fuels) generation. Currently, the focus of grid infrastructure modernization is to increase sensor deployment across the spectrum to provide wide area monitoring and utilize data analytics tools to provide for situational awareness and insights for improving the grid operations. While this is an important aspect of the future grid, there is a critical need to upgrade the aging hardware components with advanced components embedded with smart features that include communications, advanced control, protection, autonomous decision-making and cyber-secure interfaces. Grid resiliency and reliability can be much more fully realized with holistic solutions that include both hardware and system level solutions designed to handle the future grid challenges [36].

Thus, solid-state power substations (SSPS) are introduced as a solution, utilizing PE systems to significantly increase the flexibility and controllability of the conventional substation. SSPS is defined as an autonomous, intelligent grid-entity capable of power and information exchange and serves as an interface between the grid and the end user. The philosophy behind the design is to facilitate “virtual substations” in different sections of the grid and to completely automate the energy flow between the loads and sources with embedded intelligence and distributed control architecture. The design will also maximize the grid support from these entities and enable a bottoms-up approach to grid modernization. To enhance grid metrics of reliability, resiliency, power quality, affordability, and efficiency, the SSPS will be a standardized modular, scalable entity with advanced features and functions like decision making capability. The proposed concept, modular PE building blocks with applications across the entire grid, is shown in Figure 20 [36].

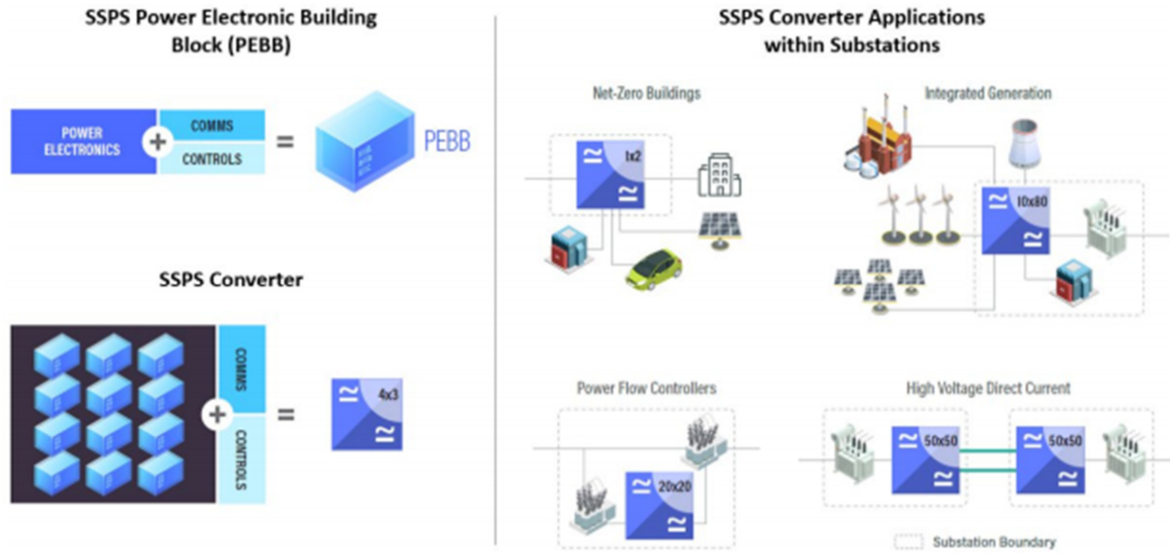

Figure 20. Vision of power electronics building blocks in SSPS.
Source: Adapted from "Solid State Power Substation Technology Roadmap," (U.S. Department of Energy Office of Electricity, 2020)

SSPS uses PE to tie together different, modern uses of the grid and re-imagines the communication and control of the future network to enable dynamic, optimized power flow and topology optimization.

Future State and Opportunities

In the roadmap for SSPS R&D released by DOE in 2020, three different solid-state power stations (SSPS) layers have been classified based on voltage and power: distribution (SSPS 1.0 up to 34.5 kV), sub-transmission (SSPS 2.0 up to 138 kV) and transmission (SSPS 3.0, > 138 kV) [36]. These three iterations of SSPS have application in different points in the electricity network and are planned to be developed over the next two decades. Table 4 summarizes the functions and features of each SSPS classification [36].

Table 4. SSPS converter classifications and features.[f]

Source: Adapted from "Solid State Power Substation Technology Roadmap," (U.S. Department of Energy Office of Electricity, 2020)

CONVERTER CLASSIFICATION	DEFINING FUNCTIONS AND FEATURES
SSPS 1.0 UP TO 34.5 KV 25 KVA–10 MVA	• Provides active and reactive power control • Provides voltage, phase, and frequency control including harmonics • Capable of bidirectional power flow with isolation • Allows for hybrid (i.e., AC and DC) and multi-frequency systems (e.g., 50 Hz, 60 Hz, 120 Hz) with multiple ports • Capable of riding through system faults and disruptions (e.g., HVRT, LVRT) • Self-aware, secure, and internal fault tolerance with local intelligence and built-in cyber-physical security
SSPS 2.0 UP TO 138 KV 25 KVA–100 MVA	+ Capable of serving as a communications hub/node with cybersecurity + Enables dynamic coordination of fault current and protection for both AC and DC distribution systems and networks + Provides bidirectional power flow control between transmission and distribution systems while buffering interactions between the two + Enables distribution feeder islanding and resynchronization without perturbation
SSPS 3.0 ALL VOLTAGE LEVELS ALL POWER LEVELS	+ Distributed control and coordination of multiple SSPS for global optimization + Autonomous control for plug-and-play features across the system (i.e., automatic reconfiguration with integration/removal of an asset/resource from the grid) + Enables automated recovery and restoration in blackout conditions + Enables fully decoupled, asynchronous, fractal systems

SSPS architectures are scalable, flexible, and extensible, and deployed in a variety of applications and use cases. The holistic design approach includes aspects of power systems, power electronics, controls, protection, converter design, mechanical integration as well as communications, controls, and intelligence. One of the key aspects of the SSPS approach is to integrate advanced components into systems of standardized modular and scalable power blocks with embedded diagnostics and prognostics. The innovations in hardware power stages address the reliability challenges of PE systems within substations and further reduce the costs of the modular substation concept.

As the SSPS concept spans across the grid network, nodes, and hubs of SSPS 1.0, the closest technology to realization, can be deployed at the consumer and distribution scale. SSPS 1.0 will operates at the lowest voltage and power levels, be much easier to deploy selectively and would have the greatest value proposition to both energy consumers and utility/ system operators. An SSPS 1.0 will perform the functions of traditional substations while providing system-wide benefits and functionalities through the integration of controllable power converters, passives, protection equipment, and measurement and telemetry, local and remote controls, and communication systems. This added functionality may ease DER integration, aid distribution system hosting capacity, and provide control and flexibility benefits.

[f] HVRT: High voltage ride through

LVRT: Low voltage ride through

SSPS 2.0 and 3.0 each have wider use across the grid. SSPS 2.0 acts as an integrated smart node within T&D systems, with the capability to handle scaling challenges as the network evolves. 2.0 also assists in the management of reverse power flows (caused by increased DER penetration), limits fault currents, and enables new grid architecture paradigms, including integrated offshore wind or subsea network applications. SSPS 3.0 builds upon the benefits of 1.0 and 2.0, expanding capabilities to any voltage level or power rating, providing a powerful tool for large-scale grid optimization. Figure 21 illustrates the domain areas of SSPS 1.0, 2.0, and 3.0 [36].

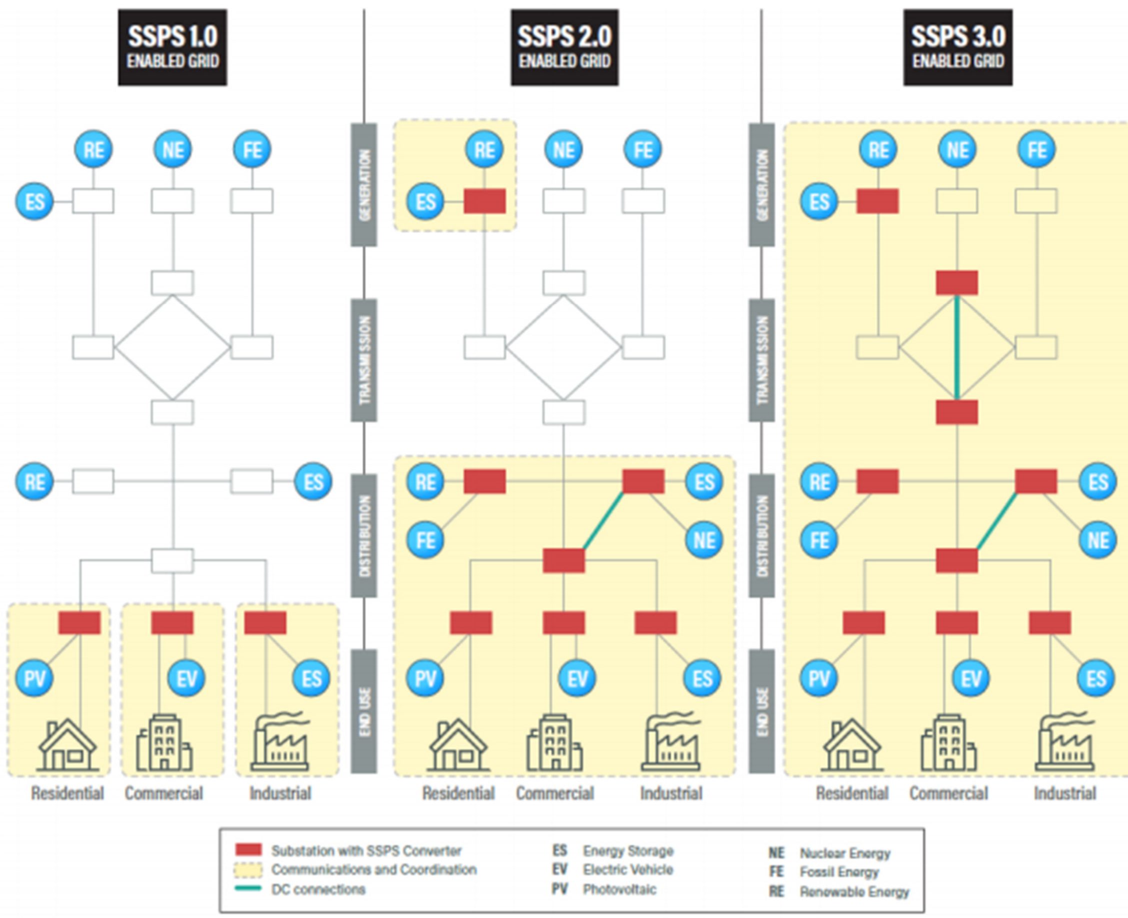

Figure 21. SSPS classifications across the grid.

Source: Adapted from "Solid State Power Substation Technology Roadmap," (U.S. Department of Energy Office of Electricity, 2020)

SSPS has the significant potential to modernize the grid and provide benefits for controllability and flexibility across a variety of generation sources and grid topologies. This will enable advanced communications and controls across all connections of the SSPS "grid node," allowing for enhanced bidirectionality and dynamic coordination across all generation sources. Fully realized implementation of advanced SSPS architectures will have benefits across every metric of grid modernization, helping to mitigate future challenges and integrate across a system with a variety of requirements [36].

Challenges

Because SSPS is early in development, implementation challenges are not thoroughly researched. However, there are some preliminary challenges that must be solved for SSPS to be integrated into the electricity delivery system:

1. The balance-of-systems costs are high for deploying new solid-state PE technologies.
2. Reliability and lifetime of PE/solid state-based equipment needs to be improved.
3. Standardized interfaces are needed for power blocks to be vendor agnostic. Domestic manufacturing of these blocks may be required for multiple applications.
4. Vendor agnostic software platforms are needed that can utilize standardized hardware from multiple vendors.
5. New grid architectures are needed that can address the growing DER source penetration load increase, especially at the edge of the grid.

R&D Opportunities

PE, in many applications, has the potential to solve the numerous challenges facing the electric grid of the future. PE is used to support the electric grid in several use cases, including different types of power flow controllers, HVDC systems, and SSPS. R&D on one type of device or innovation will benefit one or more of these application areas, as many of the challenges facing PE maturity are common to multiple use cases. Once solved, these technologies will transform the grid through reliability, resilience, and flexibility innovations. Enhanced R&D in this area will result in a future grid of flexible architectures, capable of dynamically responding to customer needs and integrating a high percentage of renewable resources.

The R&D needs for PE technologies follow a different structure than the R&D requirements for DLR and topology optimization. While DLR and topology optimization R&D recommendations include both technology and implementation, PE evolutions will require more investment in the hardware itself, within the following three areas:

1. Power Electronics Components: The building blocks of PE technologies, including fundamental technologies and materials such as controllers, power semiconductor devices, breakers, and AI platforms.
2. Power Electronics Systems: The power systems, incorporating PE, that are incorporated into full electric power systems. These include FACTS devices, protection equipment, and interconnection equipment. Computational platforms and controls integration are also required to integrate power system devices.
3. Grid Integration: Whole-grid impact evaluation considering architectural considerations, use cases and demonstrations for PE technologies.

Figure 22 summarizes the specific R&D needs within the three listed areas.

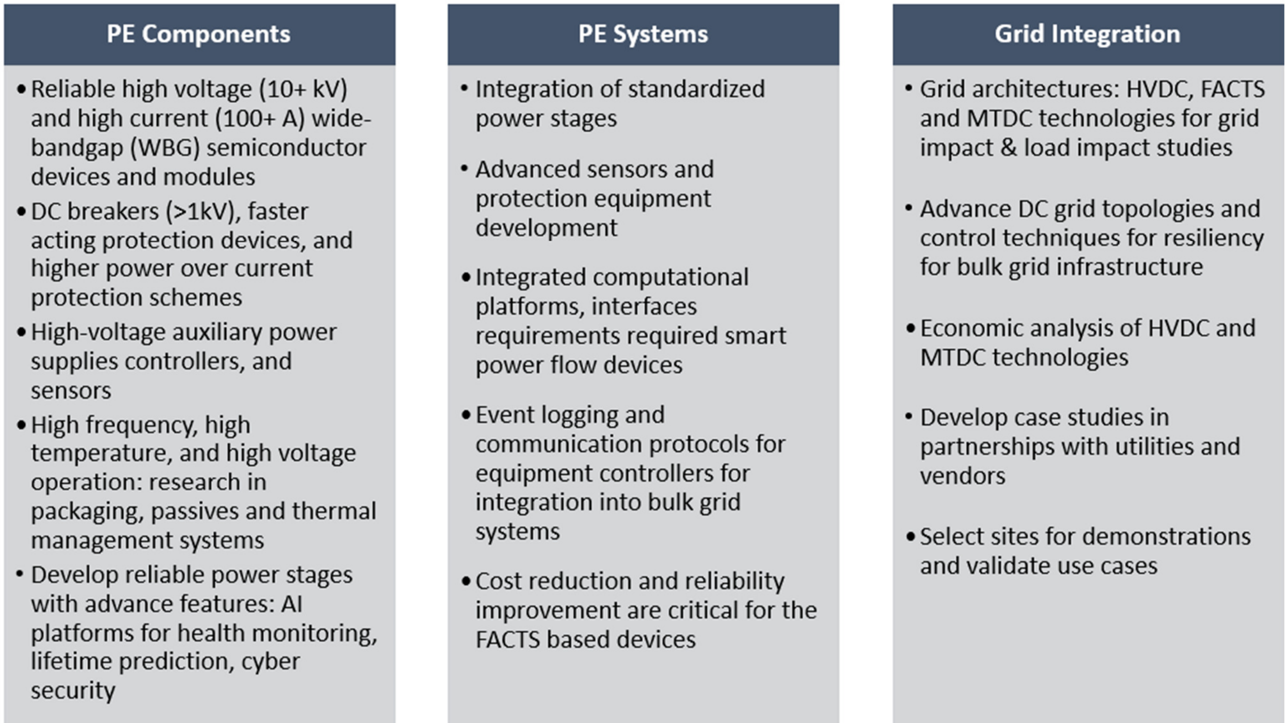

Figure 22. R&D areas for power electronics.

Source: U.S. Department of Energy, Office of Electricity

DOE's TRAC program is the primary mechanism within the Office of Electricity to support grid hardware and power electronics for the future electricity network. There are other programs across DOE that also support the R&D of advanced power electronics, including the PowerAmerica consortium through the Advanced Manufacturing Office that brings together companies and universities to support research and workforce development for advanced wide bandgap (WBG) semiconductors [37]. ARPA-E also has an extensive power electronics components and systems portfolio which aims to address the specific R&D needs to solve the numerous challenges facing the electric grid of the future [38]. These programs include ARPA-E's PNDIODES program, to develop transformational advances in WBG semiconductor devices, the CIRCUITS program, to accelerate the development and deployment of a new class of improved power converters [39], and the BREAKERS program, to fill the gap in Medium Voltage Direct Current (MVDC) safety and protection systems [40]. MVDC circuit breakers would enable new grid architectures/paradigms, such as DC distribution and microgrids, to accommodate the loads and sources required in the future. These DOE programs demonstrate the significant impact of improved R&D on power electronics.

IV. Future Grid R&D Needs

In summary, to achieve a future, modernized grid, there are three main paradigms that require enhanced R&D. The transition from (a) static line rating to dynamic line rating, (b) firm grid topologies to flexible ones, and (c) passive grid hardware to dynamic hardware all work concurrently to achieve the future grid paradigm.

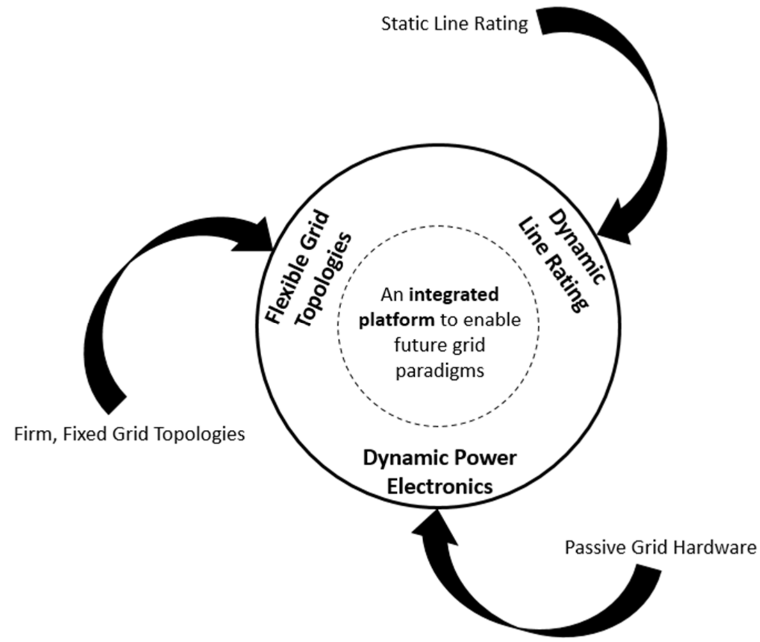

Figure 23. Future network technology paradigms.
Source: U.S. Department of Energy, Office of Electricity

These technology transitions have barriers to widespread acceptance. Across each paradigm shift, even in instances where the technology is mature, balancing authorities and transmission owners may be disinterested in adoption for a variety of reasons. Decision-makers may lack insufficient incentives to adopt new technologies that have not been thoroughly validated through studies or deployments. Studies can illustrate the costs and benefits of such technologies, while deployments can validate the impact and provide confidence to upgrade some part of the system. In other cases, the technology requires further maturity: the application of power electronics with grid hardware still has room to develop, DLR has several implementation challenges, and large-scale topology optimization also requires upgraded, computational infrastructure or advancements for more efficient models. All system improvements come with challenges for cybersecurity, operator training, and some level of risk.

A detailed list of integration and adoption challenges is found in DOE's 2020 *Advanced Transmission Technologies*.

Successfully facilitating the listed transitions will yield the benefits of a future grid: flexible, reliable, resilient, secure, affordable, and sustainable, and with the ability to support the future priorities of customers and stakeholders. Achieving those characteristics will require tackling the many challenges facing the future grid, caused by customer needs and external factors. To support the transformation and mitigate barriers caused by increasing variability, aging infrastructure, congestion, unpredictable event, and cybersecurity, R&D is required. As summarized in Figure 24, prioritizing R&D concentration areas will enable the critical technology paradigm shifts needed to solve the challenges facing the future electric network and meet the dynamic needs of the system.

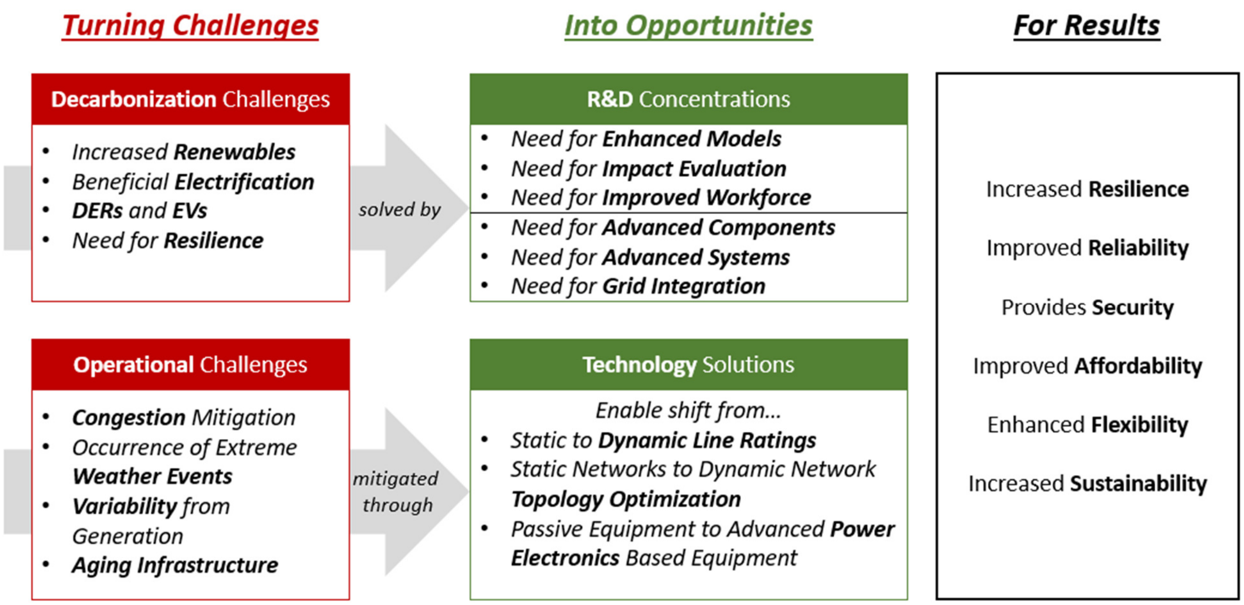

Figure 24. R&D areas of next-generation grid technologies.
Source: U.S. Department of Energy, Office of Electricity

V. Conclusion

The electricity delivery system is rapidly changing. Historically, the electric grid was a monolithic, static system capable of transporting electricity in one direction from large, centralized resources. As customer needs have evolved to dynamic, distributed, and variable loads, so too must the system that transports power. To meet the evolving needs of the grid and enable its transformation to a future network, technology solutions must be deployed that can mitigate or solve the many challenges of tomorrow's system.

While there is a large array of technology solutions to enable the future electric network, three specific paradigms are highlighted in this report: the transition from static to dynamic line rating, the transition from fixed to variable and agile topologies, and the transition from passive grid hardware to power electronics. These three technology evolutions, while feasible, each have their own challenges and specific R&D areas to enable the transformation. DLR and topology optimization face barriers such as data inaccuracies, adverse impact on infrastructure, market readiness, and economics of implementation, and key R&D areas to solve these problems include enhancing models and data, evaluating impacts, and developing the workforce. For Power Electronics technologies, including power flow controllers and SSPS, R&D areas include the three main applications of PE: components, systems, and grid integration. Emphasizing all three will bring costs down and solve key implementation issues that will allow the future grid to benefit from the reliability, resilience, and flexibility benefits that PE systems promise.

Prioritizing R&D in these technologies is critical for a successful, future grid. Solving the challenges and barriers associated with these technologies will result in a modernized electric grid that is reliable, resilient, secure, affordable, flexible, and sustainable. Achieving renewable energy milestones and decarbonization goals, reaching resiliency goals, and meeting dynamic customer needs will not be possible without the R&D advancements needed to support them.

VI. Appendix

Appendix A: Grid Views

The evolving grid is also increasing in complexity. The grid can be defined as an Ultra-Large-Scale (ULS) system, featuring six intricate major layers that were generally not designed with interconnection and long-term planning in mind. These layers, summarized in Figure 25, include the tangible, such as electricity and communications infrastructure, as well as the intangible, such as market and regulatory structures. Each layer of the grid contains its own set of considerations and interdependencies, and a holistic view is required to understand how each one contributes to the complex system that delivers power across the country. The dependencies and relationships increase the total system complexity by orders of magnitude.

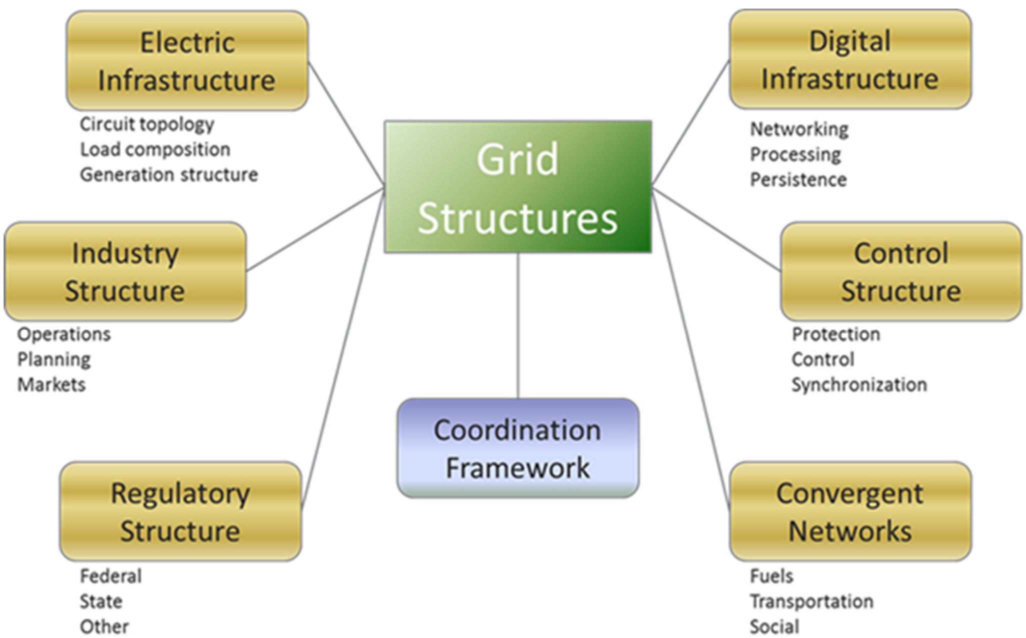

Figure 25. Grid structures.

Source: Jeffrey Taft, Pacific Northwest National Laboratory

There are other alternate ways to view and illustrate the grid. For example, Figure 26 displays the major technology priorities in the electric network. These technologies align with those outlined in this report, as well as other important solutions that support all six characteristics of a modernized grid.

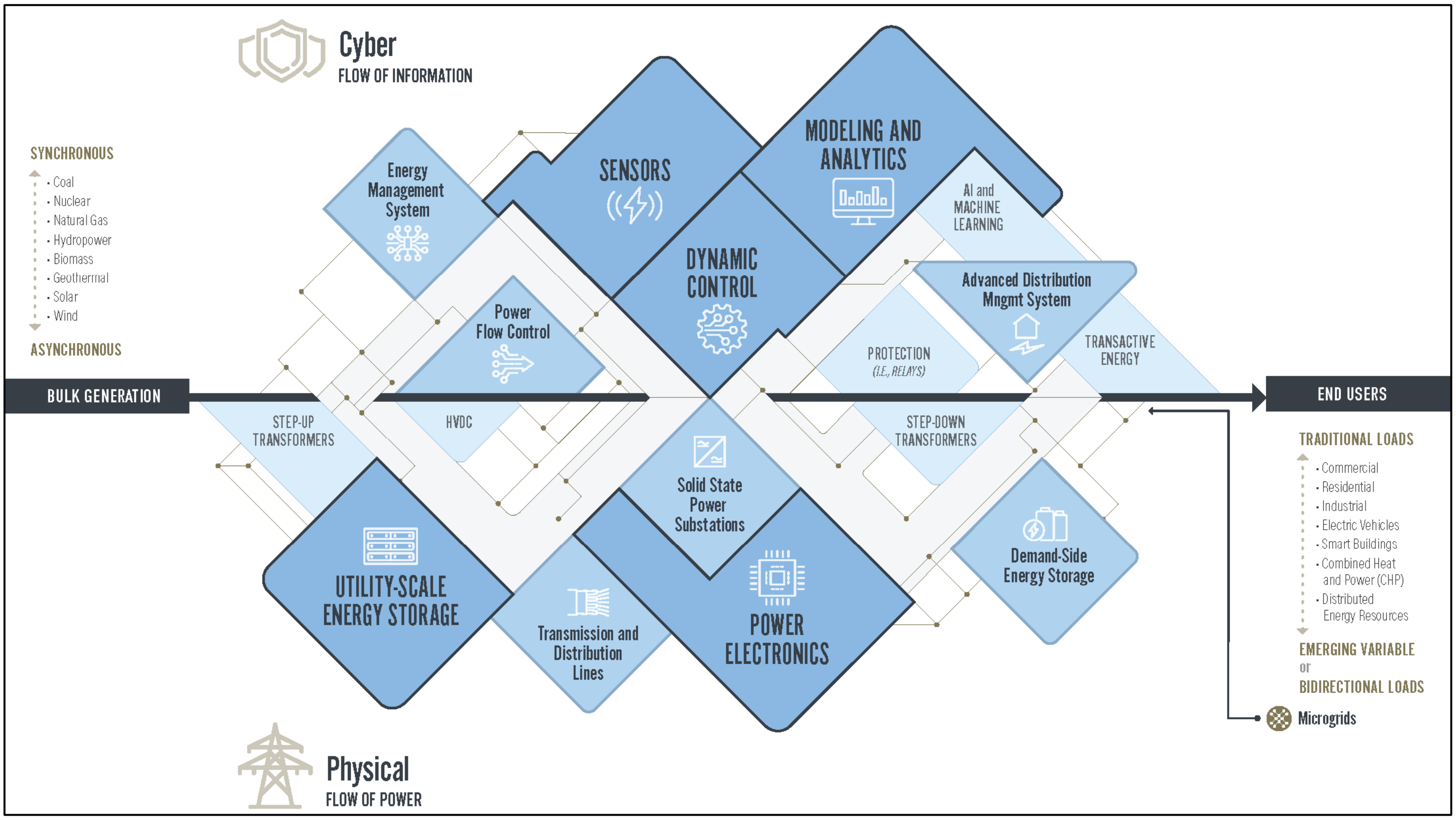

Figure 26. Technologies in the electric network.
Source: U.S. Department of Energy, Office of Electricity; ICF

Figure 27 shows an extended set of categories for the layers in the grid. The purpose of including this figure is to further illustrate the complexity of the electric system, and the dozens of factors that must be considered in the transformation to the future network.

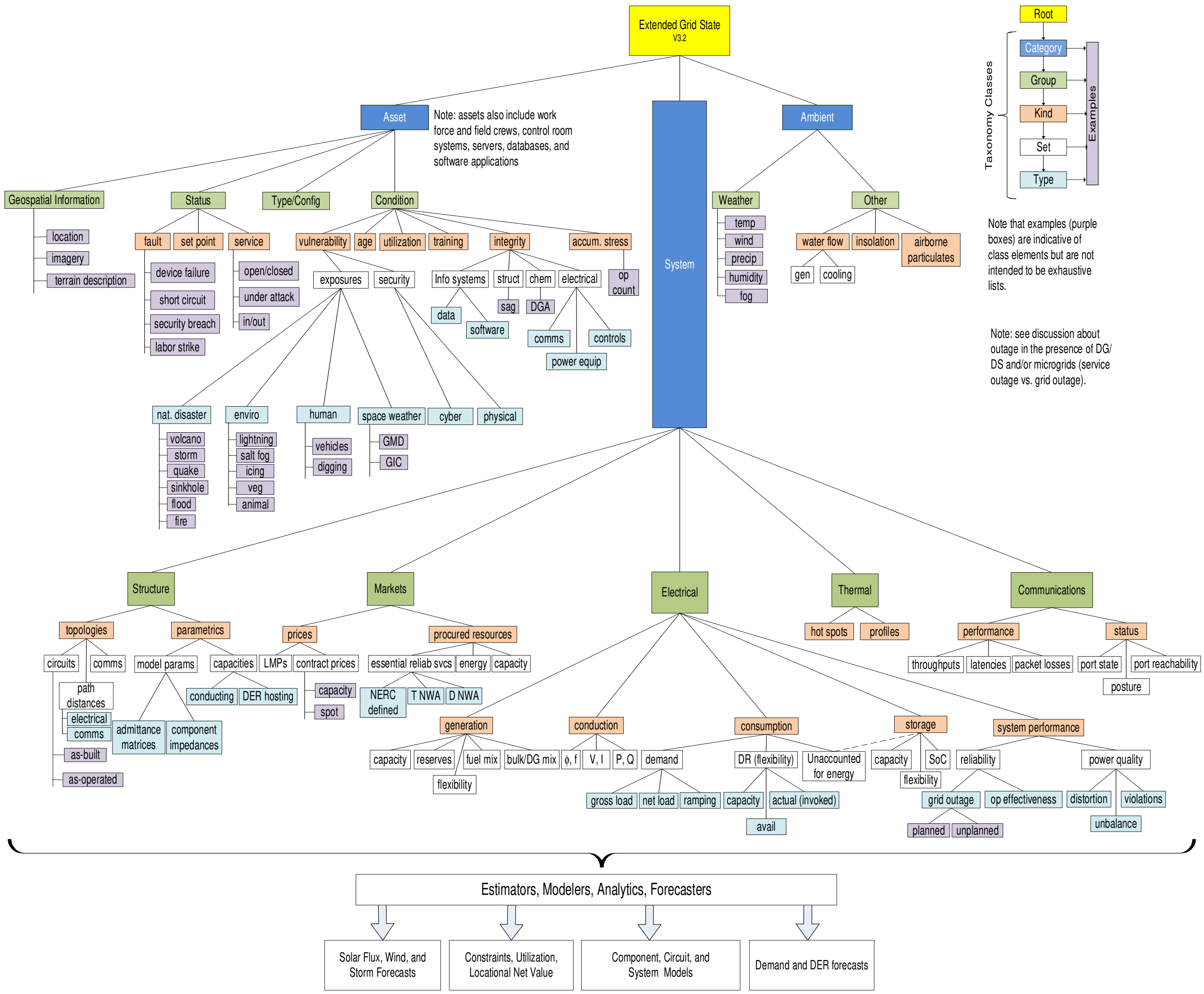

Figure 27. Extended Grid State Taxonomy.

Source: Adapted from "Extended Grid State Definition Document," (J. Taft, E. Stewart and Z. Li, 2019)

Figure 28 displays a third view of the grid. This view displays the cyber-physical layers of the grid as a “platform,” where core competencies and technologies support different advanced applications. More information on this grid view can be found in DOE’s Modern Distribution Grid (DSPx), Decision Guide Volume III [41].

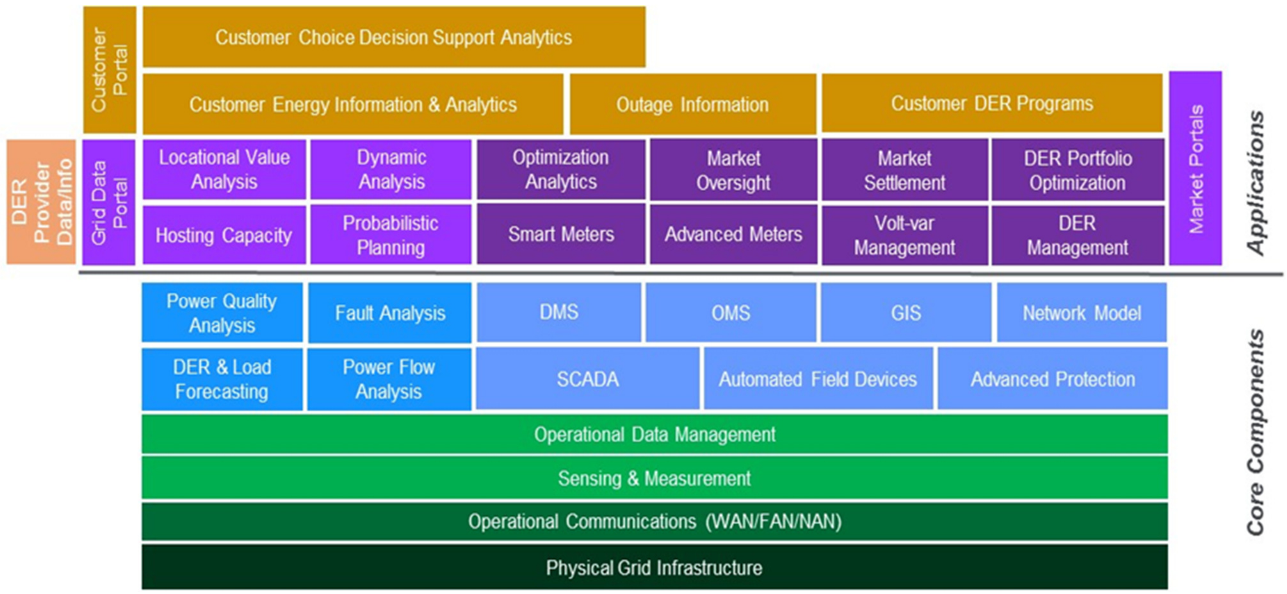

Figure 28. Cyber-physical platform of the grid.

Source: Adapted from "Modern Distribution Grid: Volume III," (DOE Office of Electricity, 2017)

There are many ways to depict the complex set of interdependencies, systems, stakeholders, and technologies that lead to reliable operation of the electric network.

Appendix B: Trends and Challenges Driving Transformation

There is a dramatic structural transformation occurring today that will affect the production, delivery, and customer interaction of the complex electricity delivery system. The grid is rapidly transitioning from a system capable of one-way power flow from large, centralized resources to one that includes a wide range of futures and changes across all scales: on the largest interregional transmission level to the smallest distribution level. This section illustrates the many trends driving this transformation as well as the major challenges, caused by these trends, that future grid architectures will face.

When examining the functions and capabilities of the future electric network, it is important to view the future system as a set of possible architectures rather than any one fixed system. There are many ways the grid can and will evolve from its current state, and thus many futures of the electric network. Depending on regional factors, generation mixes, technology advancements, and policy, different areas of the future grid may evolve and operate completely different than others. For example, some areas may benefit most from a highly decentralized grid dominated by DER and distribution management systems, while others may maintain large-scale generation facilities and, such as in the case of centralized renewable resources, require extensive transmission build-out and storage to support them. There are many axes on which different segments of the future network may be evaluated, and Figure 29 displays some possible futures across them.

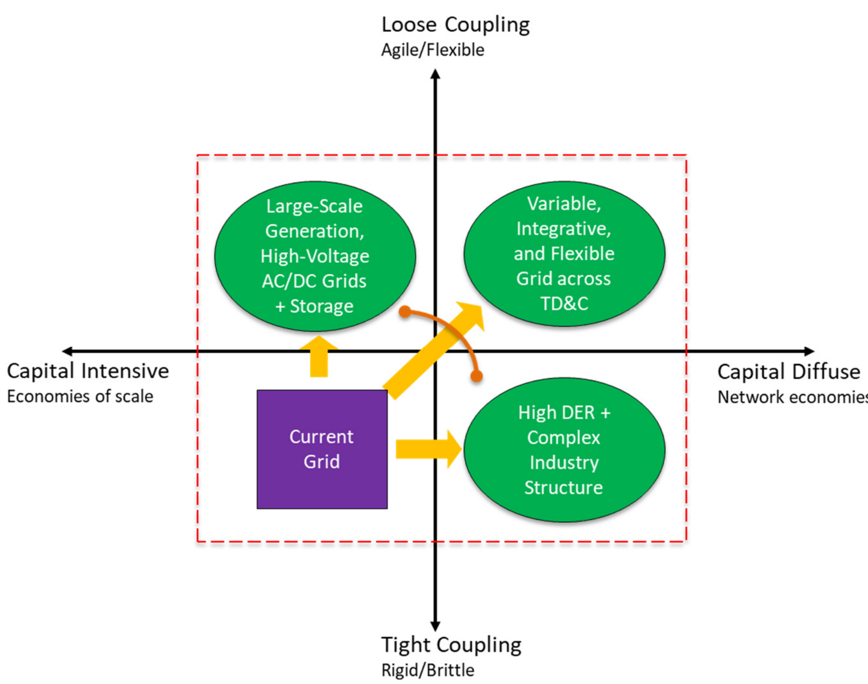

Figure 29. Possible futures of the electric network along two axes.
Source: U.S. Department of Energy, Office of Electricity

The trajectory of today's electric grid is highly variable and different regions will respond differently to its trends, challenges, and technology advancements. Without sufficient investment in the future electric network, the electricity delivery system may be unprepared to solve the challenges driven by future trends and thus not able to support a dramatic transformation.

Trends of the Electric Grid

There are several drivers that are dictating the direction of today's electric grid. These trends, often the impact of policy, customer interest, and economics, are critical to defining how technological solutions can solve the pressing challenges of the transforming grid.

Transition to Low-Emission Generation Sources. Traditionally, fossil sources such as coal and natural gas have powered the U.S. and the world. However, in recent years, there has been a great push to transition away from coal in favor of low to zero carbon emission electricity sources such as natural gas, solar power, and wind. Figure 30 displays two different views of this changing energy mix, demonstrating how renewable energy and natural gas sources have increased while coal has decreased. Figure 31 displays that in 2019, renewable sources generated more power than coal did in the U.S. for the first time ever [42] [43]. These trends are expected to continue: planned added generation capacity in 2021 is predominantly renewable as costs of renewable resources continue to plummet [44] [45].

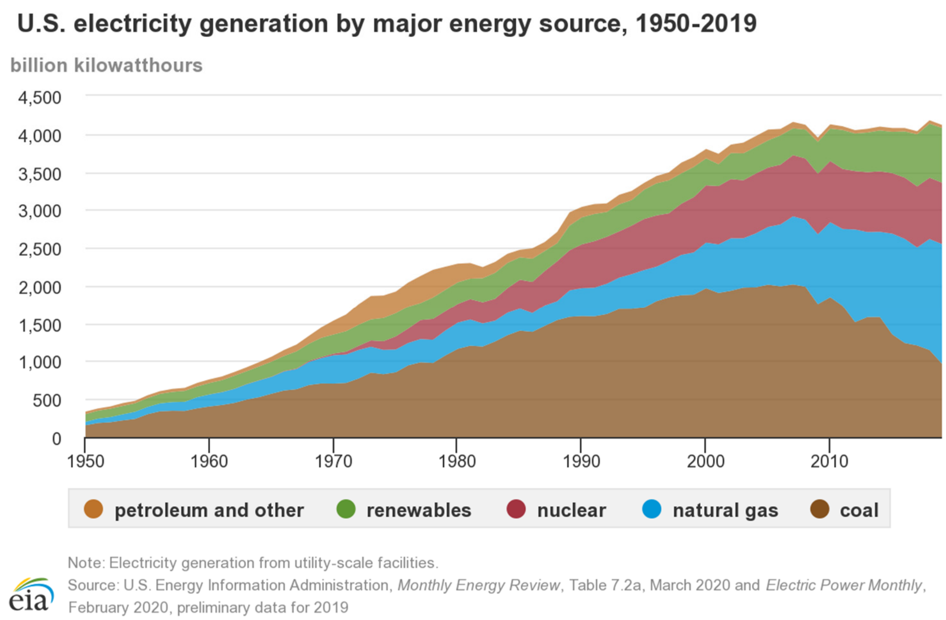

Figure 30. U.S. electricity generation by major energy source (1950-2019).
Source: Adapted from "Electricity explained Electricity generation, capacity, and sales in the United States," *https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php* *(EIA, 2020)*

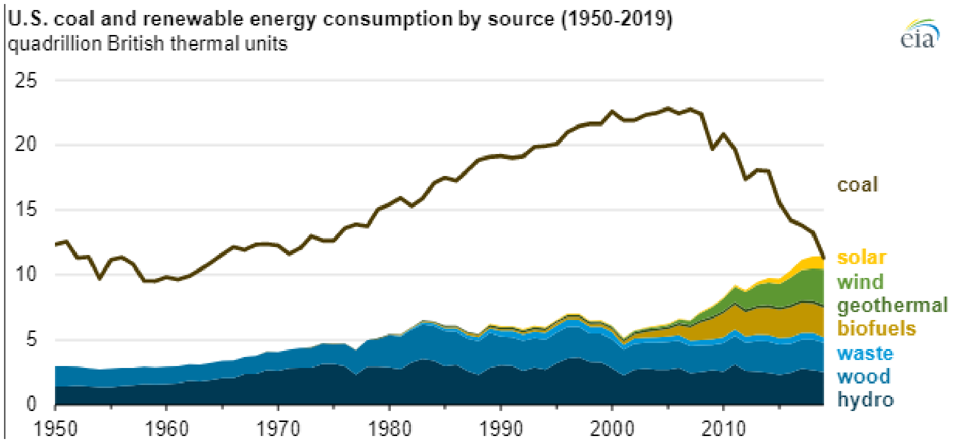

Figure 31. U.S. coal and renewable energy consumption by source (1950-2019).

Source: Adapted from "U.S. renewable energy consumption surpasses coal for the first time in over 130 years," https://www.eia.gov/todayinenergy/detail.php?id=43895 (EIA, 2020)

As of August 2020, 37 states and the District of Columbia have passed renewable portfolio standards or goals, policies that encourage renewable implementation for a given region or territory. Furthermore, dropping costs and other drivers (including state and federal tax credits, net metering, and corporate sustainability reporting) are making renewable energy sources increasingly attractive for customers [46]. This trend has impacts on the bulk power system, and will require improvements to system flexibility, transmission capacity[g] [47], and planning to ensure continued reliability [48].

Increased Customer Participation in Grid Markets. Historically, electricity customers had no option to directly participate in the market structure that delivered them power: electricity was produced at generation facilities, transported across transmission lines, and delivered over distribution lines [7]. However, more recently, customers have been given the option to disrupt this flow by producing electricity through distributed energy resources. DER are a set of technologies that produce energy or modify load within distribution systems. Typically, these systems are less than 10 MW and may include photovoltaics (such as rooftop solar), fuel cells, wind turbines, microturbines, and energy storage systems, and may supply all or some of the power to a customer [49]. In most cases, these customers are still connected to the grid and must purchase some power from the grid when DER generation is not sufficient to meet their demand. DER users may also, in some regions, sell back excess DER power generated to grid operators. This option makes DER deployment more attractive for some customers but increases complexity for grid operators [50].

DER have traditionally made up a very small percentage of overall load across the U.S. However, projections such as the one in Figure 32 by Wood Mackenzie in 2020 demonstrate the rapid growth of DER across the U.S. Despite a projected dip in 2020 due to COVID-19, they estimate the DER market in the U.S. will reach 387 GW by 2025 [51].

[g] Bulk renewable power generation requires a large physical footprint and, as a result, must be located far the densest urban areas that require the most power. This effect highlights the need for enhanced transmission capabilities, more than exist on today's system.

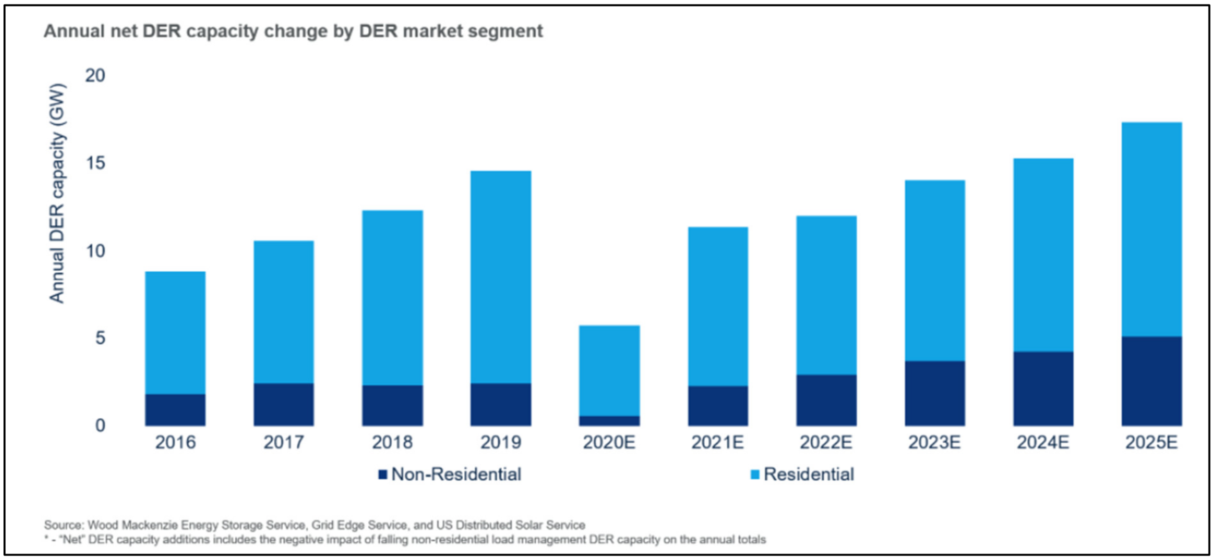

Figure 32. DER capacity as percentage of total generating capacity.
Source: Adapted from "The next five years will see massive distributed energy resource growth," *https://www.woodmac.com/news/editorial/der-growth-united-states/ (Wood Mackenzie, 2020)*

This trend is caused by several factors, including falling technology prices, state and federal policies, and customer demand. In September of 2020, FERC issued Order 2222, which provides a pathway for DER customers and aggregators to directly participate in wholesale energy markets. While this order makes the intricate process of operating the grid even more complex, it further encourages DER deployment [52]. Already, projections show significant DER development expected in 2021 [53].

This trend will continue to significantly impact the grid. When used for power system services, these technologies may provide reliability and load shifting benefits for the customer and excess power generated may assist power flow for the operator when optimized [54]. However, these devices and systems also increase uncertainty for grid operators because of the requirement to incorporate less predictable, bidirectional power flow. This transition from unidirectional to bidirectional flow adds tremendous uncertainty for those who manage the grid and underscores the importance for advancements in distribution system management and optimization.

Integration of Digital and Communication Technology. Advancements in smart grid technology are transforming the grid's controls and communications. Distributed sensors, two-way communication technologies, and advanced software solutions are all modernizing how the grid is modeled and optimized, and yield greater efficiency, resilience, security, and lower costs [55]. Such technologies also enable greater demand response, in which customer incentives and advanced technologies, such as sensors and advanced metering infrastructure, reduce or shift times of peak electricity usage. Demand response is considered a significant grid asset, especially during periods of high stress, and the customer incentives enabled by advanced digital and communication technologies are valuable to grid reliability [56]. Improvements made to the "Smart Grid" set of innovations will continue to modernize and improve many parts of the grid and facilitate the future electric network.

Rapid Electrification of Transportation and Buildings. The automotive industry and buildings (residential, commercial, and industrial), as well as industrial processes and facilities, are experiencing the effects of increasing electrification. This trend is known as "Beneficial Electrification" for the many benefits it brings customers [57], and it also offers growth in electric sector revenue and the opportunity for more investment in infrastructure. EVs, which can feature tremendous efficiency and emissions benefits for customers, are generally powered by grid-connected electric charging infrastructure. While the benefits to consumers are numerous, concentrated clustering of EV deployments could have large impacts on the distribution grid due to the need for substantial new infrastructure and the rapid, and sometimes variable, dispatch requirements at peak demand [58]. Thus, large scale coincident EV charging could challenge grid planning and operations in meeting those high loads [59]. EVs represented a relatively small percentage of the total market share of vehicles in 2020, but they are projected to significantly increase over the next several years. One projection, in a report by EPRI, found U.S. adoption of plug-in electric vehicles as significant as over 50 percent by 2040 in a "High" scenario, as seen in Figure 33 [60].

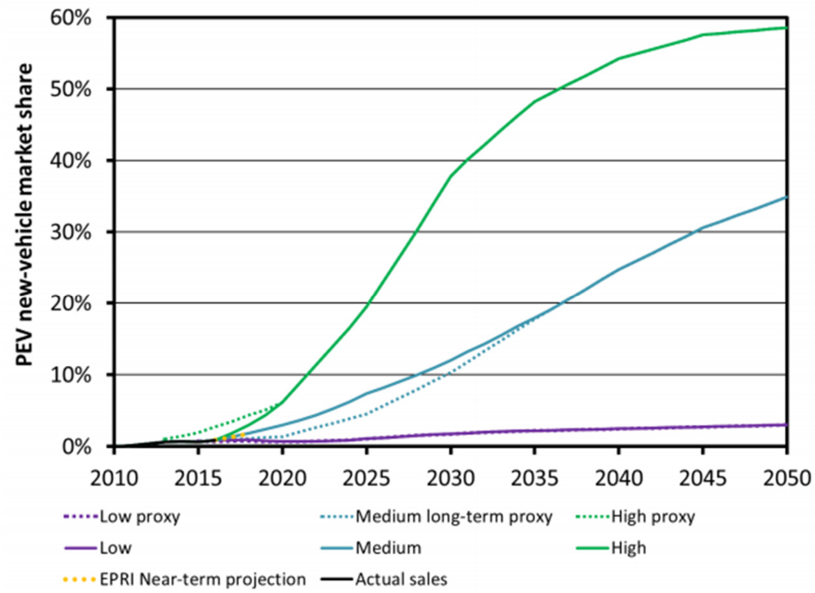

Figure 33. U.S. PEV Adoption Projections.

Source: Adapted from "Plug-in Electric Vehicle Market Projections Scenarios and Impacts," (M. Alexander, EPRI, 2017)

Buildings are also experiencing the effects of electrification. In this context, electrification refers to the substitution of traditional combustion-fueled technologies for electric equivalents. For residential buildings, this may mean space and water heating systems. For industry, this could include electrically powering any number of processes traditionally fueled by combustion. While electrified buildings have some barriers, such as high capital costs and consumer acceptance, there are many benefits to electrified buildings, including greater load management flexibility, reduced emissions/pollution, and improved power quality [61]. Some regions are implementing policy to push for increased electrification. Approximately 30 U.S. cities and counties have passed ordinances to require or encourage newly constructed buildings to be all-electric, and California has passed several incentives to encourage customers to consider electric heat pumps and other low-carbon building technologies [62]. As this trend of electrification continues, it has the potential to benefit the grid through ancillary services and flexibility, although greater convergence with grid operations increases complexity and introduces new challenges into the system [61].

Emphasis on Grid Resilience. As the electrical grid both increases in complexity and continues to prove critical for every aspect of life, the demand for grid resilience, the ability of the electric grid to respond and react quickly to disruptions, is growing. Integrated resilience planning and strategy development is increasing as a priority area as concern grows over the impacts of extreme weather events, worsened by climate change, and attacks on the grid. As these events cost billions of dollars and risk security for all customers, new focus is placed on a grid that can respond to these events more effectively [63]. For example, DOE's North American Energy Resilience Model (NAERM) aims to improve system resilience through informing regional strategies, illustrating the prioritization and demand for grid resilience [64].

Major Challenges

As the electric grid continues the trends just outlined, it must account for several major challenges that, if not addressed, threaten the reliability, resilience, and security of the future network. Some of these challenges are caused directly by the outlined trends, while others are independent events. All must be considered.

Each of these challenges demonstrate that the future needs of the electric network may not be met with the infrastructure that currently exists. As the transformation to the future grid continues, these key challenges faced by the network of the future represent the urgency of prioritizing the electric grid and the risks associated with neglect.

Increasing Generation Uncertainty. It is a significant challenge for grid operators today to manage the changing loads across different times of day, seasonal demands, and unpredictable events. Grid operators must, in real time, successfully balance factors such as different power demand at different times of the day, the effect of heating and cooling system demand changing based on weather and season, and potential line outages caused by unforeseen events. Reliable electricity delivery is a challenging real-time balancing act requiring great effort from those who manage it [65].

The real-time power balancing problem becomes much more complex when considering rapidly emerging generation sources such as variable and inverter-based resources (e.g., renewables), and new loads such as those resulting from EV deployment, DER, and other sources of demand variability such as microgrids. These all add uncertainty to both ends of the power balancing equation [66]. As an example of the impact of variable generation sources on grid operations, Figure 34 shows ERCOT's published Wind Integration Reports for two adjacent days, May 6, 2021 and May 7, 2021. The comparison shows that load varies predictably while wind generation has significant fluctuation that differs greatly between the two adjacent days. Even with tremendous growth in wind, there may be times of significant under-production or over-production based on the variable nature of wind strength [67].

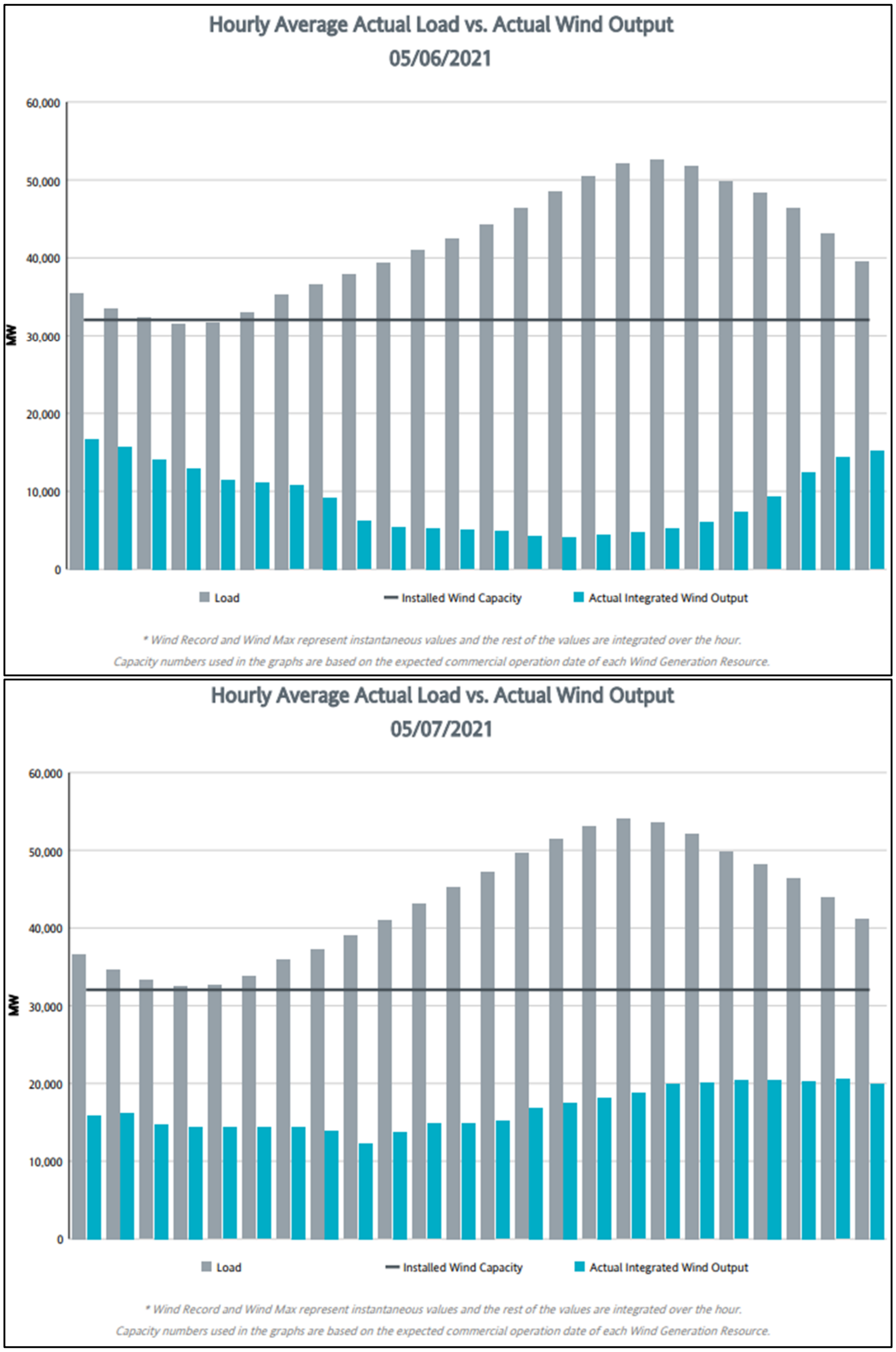

Figure 34. ERCOT Wind Integration Reports May 6th, 2021 vs. May 7th, 2021.
Source: Adapted from "Wind Integration Report, May 2021," (ERCOT, 2021)

Generation uncertainty challenges can be mitigated by use of energy storage systems. However, long-duration energy storage solutions are still in development, and the integration of such systems increases the operational complexity.

Aging Infrastructure. Most transmission & distribution lines in the U.S. were constructed in the 1950s and 1960s and thus many have already exceeded their 50-year lifespan [68], while some components in the grid are over a century old [5]. To achieve the reliability required in a modernized grid, replacing these old systems is essential. Old, aging infrastructure is prone to failure, both by intentional attacks and extreme conditions, and decision-makers are often forced to opt for temporary, less expensive fixes instead of longer-term solutions and investments.

A 2020 study performed by ASCE found that current investments in grid infrastructure are not sufficient to meet future needs. In their *Failure to Act* report, ASCE found that the U.S. is facing a shortfall of $208 billion in grid infrastructure investments by 2029, and $338 billion by 2039. If this investment gap is not remedied, there is a projected job loss of 287,000 by 2029 and 540,000 by 2039, as well as a cost to each American household of $563 per year [68].

Quantitative analysis supports that investments in aging grid infrastructure are critical and, at present, insufficient. This challenge will compound as infrastructure ages further.

Congestion. System congestion occurs when a power system component must operate within a certain limit so that reliability is maintained. For example, a transmission line's current capacity may be capped so that it does not exceed a thermal limit and malfunction. Transmission congestion refers to the economic impacts of reaching these system limits, such as when a transmission line at-capacity needs to transport more power and a non-optimal delivery path must be taken to maintain reliability [69]. These mitigation techniques are known as congestion management, and even performed optimally, still yield significant costs for RTOs/ISOs, utilities, and customers.

In 2016, DOE estimated the cost of congestion to be $4.8 billion [11], which annually costs RTOs/ISOs hundreds of millions of dollars [69]. Another challenge with congestion comes in the form of curtailment, where resources may have to operate at a lower level than their optimal output, causing wasted energy potential. Congestion is a major cause of curtailment and remains a challenge that, with the right technology solutions, represents a substantial source of potential cost savings for the electricity industry and customers [70].

Unpredictable Events & Disasters. Natural disasters such as hurricanes, earthquakes, and wildfires have the potential to cause disaster for grid operations. Even though grid operators control the grid to contingency standards, serious events have the potential to cause widespread blackouts and impart tremendous costs. Wildfires, storms, and extreme weather may lead to widespread outages and damage equipment, which will accrue extensive costs in repair and restoration costs after an outage. Flooding and other long-term or permanent disasters may also force the very expensive relocations of people and infrastructure [71].

In August 2020, California experienced rolling blackouts that affected hundreds of thousands and customers. These blackouts occurred during an intense heat wave, which led to greatly increased power demand and insufficient in-state and imported supply, significant impacting reliability [72].

In February 2021, extreme cold led to grid equipment malfunction in Texas that caused over 3 million people to face prolonged power outages during the crisis [73]. These events, and many others, highlight the significant risks posed by unpredictable disasters on the grid. And, as climate change intensifies, extreme weather events and their effect on the grid will continue to worsen.

COVID-19 is an example of an unpredictable event not related to extreme weather. A study published by NERC at the onset of the pandemic in Spring 2020 lists potential reliability considerations of increased uncertainty in demand projections and forced outages or limited supplies caused by workforce unavailability [74]. Unpredictable events of many types have the potential to create significant problems for grid operations, affect millions of customers, and cost billions of dollars.

Cybersecurity. Cybersecurity remains a central concern for the electric grid. In 2016, the Department of Homeland Security published a study which found that for six years, the most-targeted U.S. critical infrastructure subsector was energy. In May 2021, the Colonial Pipeline faced a major cyberattack and halted operations for several days. This attack significantly impacted transportation fuel supply across the Southeast United States, demonstrating the substantial impact of such attacks on energy infrastructure [75].

In recent years, cyberattacks on the power grids or generation of Ukraine, Saudi Arabia, and South Africa caused significant system damage and blackouts. To quantify the risk, a study performed by the insurance company Lloyd's of London concluded that a successful, wide-ranging cyberattack on the power grid in the Northeastern United States could cost between $243 billion and $1 trillion to fully recover [76]. And, as more digital and grid-edge devices are integrated into the electricity delivery system, more risk pathways open and the potential for a cyber-attack increases [77]. Cybersecurity remains a pressing concern and a key challenge for the future grid to solve.

Appendix C: Dynamic Line Rating

Figure 35 displays the numerous factors that contribute to determining the dynamic line rating of a given line, and an approximation – given the value of each variable – of the thermal limit of the line at each point in time [17].

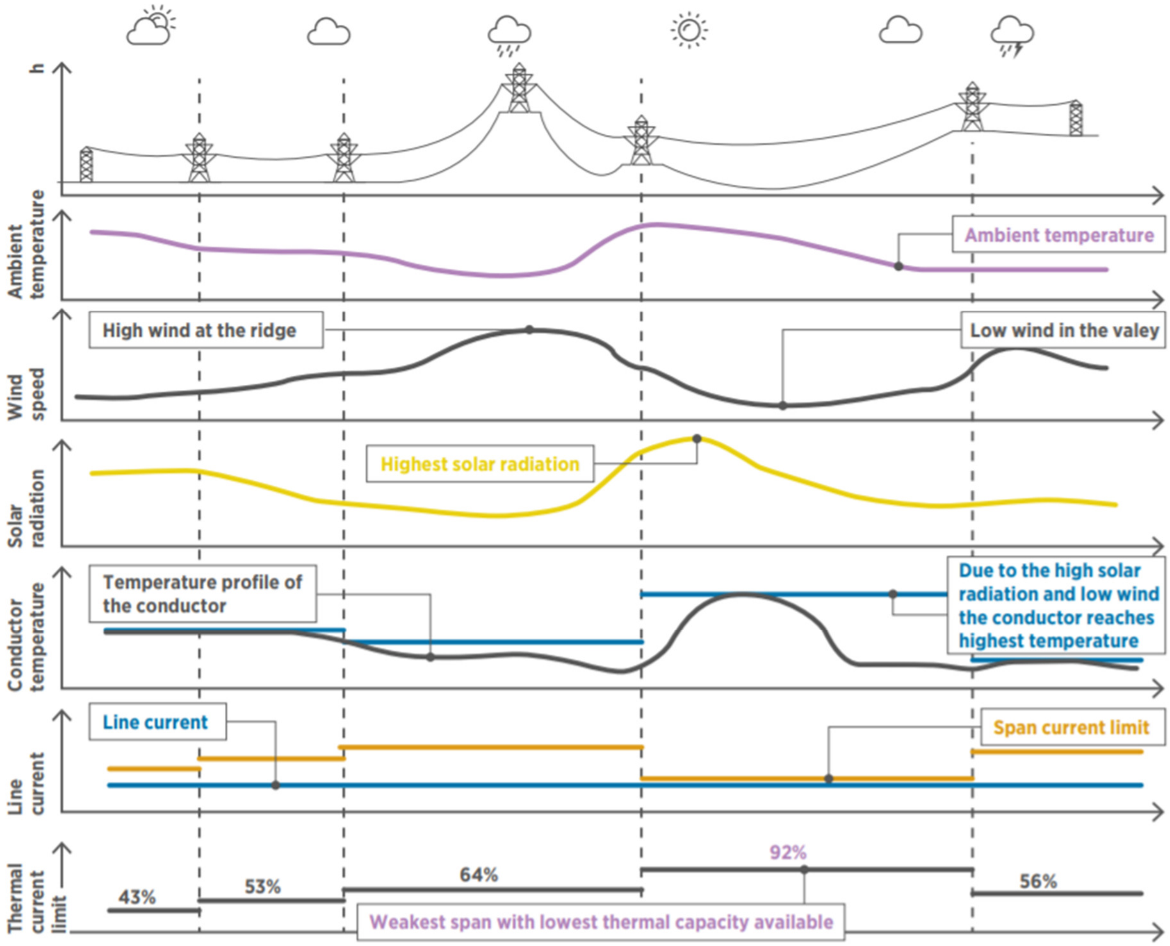

Figure 35. Variables impacting dynamic line rating.

Source: Source: Adapted from "Dynamic Line Rating Innovation Landscape Brief," (International Renewable Energy Agency, 2020)

Table 5, from DOE's 2019 *Dynamic Line Rating* report, displays the different types of DLR approaches and their advantages and disadvantages.

Table 5. DLR approaches advantages and disadvantages.

Source: Adapted from "Dynamic Line Rating," (U.S. Department of Energy Office of Electricity, 2019)

	Measurement Parameter	Approach	Advantages and Disadvantages
Direct Conduct		Ground-based Sensor	Devices like infrared thermometers/cameras are used to measure conductor temperature from the ground. + Temperature can be measured directly. + No line outage is required.

			- Difficult to verify and validate calibration. - Susceptible to physical interference, which may cause inaccurate readings.
	Temperature	Line-mounted Sensor	Thermocouples or thermistors are affixed onto the conductor to measure its temperature. + Temperature can be measured directly. - Single point of measurement. - May require line outage during installation or maintenance. - Difficult to verify and validate calibration
	Tension Monitor		Devices are attached to the conductor to measures the mechanical force between the line and the structure. + Monitors physical characteristics of a conductor and can benefit asset management (e.g., ice loading). - Requires line outage to install.
	Sag	Ground-based Sensor	Cameras monitor the distance a line has sagged. This is accomplished through image processing techniques, or with a target affixed to the line that the camera tracks. + No line outage is required. + Monitors physical characteristics of a conductor and can benefit asset management. - Difficult to verify and validate calibration.
		Line-mounted Sensor	Devices that measure the inclination and vibration of a line to determine the amount the line has sagged. + Monitors physical characteristics of a conductor and can benefit asset management. - May require line outage. - Difficult to verify and validate calibration.
	Clearance	Ground-based Sensor	Devices measure the electric fields emitted from a line to determine its distance above ground. + No line outage is required. - Susceptible to electromagnetic interference
		Line-mounted Sensor	Devices mounted to the conductor that use sonar, light detection and ranging, or a range finder to measure its distance to the ground. + Monitors physical characteristics of a conductor and can benefit asset management. - Requires line outage to install. - Twisting lines can rotate the device, causing incorrect readings.

	Measurement Parameter	Approach	Advantages and Disadvantages
Environmental Parameter Monitoring	Weather	Numerical methods	Given historical weather data and other data sources, predicts weather conditions through computation and mathematics. + Minimal to no specialized hardware required. - Real-time predictions are error prone.
		Direct-measured	Weather-station sensors measure wind speed, wind direction, temperature, and solar radiation. + Environmental parameters can be directly measured. - Many weather stations required to monitor large area.
		Physics model with direct-measured	A computational fluid dynamics model uses analysis of the terrain to map wind speed and direction from weather stations data to adjacent areas. + A single weather station can effectively monitor a much larger area. - Models take additional time to run. - Requires large amount of geographic data.
	Conductor Replica		Device uses a conductor material, placed close to and in the direction of the line to be monitored, as a proxy for the line. The material's temperature is measured while it is heated electrically to determine the ambient cooling conditions. + Does not require a line outage. - Difficult to verify and validate calibration

Appendix D: SSPS

Table 6 displays the different types of conventional substations, their input and output, and their general purpose. Table 7 describes the devices found within substations, and their function. Both tables are sourced from DOE's 2020 Solid State Power Substation Roadmap [36].

Table 6. Different categories of conventional substations.

Source: Adapted from "Solid State Power Substation Technology Roadmap," (U.S. Department of Energy Office of Electricity, 2020)

Substation Category	Substation Types	Input	Output	General Purpose
Generation	• Generator Step-Up • Non-Inverter Based Renewables	Generation Facility	Transmission System	Connecting generator electric power output

Substation Category	Substation Types	Input	Output	General Purpose
Transmission	• Network • Switching	Transmission System	Transmission or Sub-Transmission Systems	Ensuring reliability of electric power delivery
Distribution	• Step-Down	Transmission or Sub-Transmission Systems	Distribution System	Ensuring reliability of electric power delivery and regulating feeder voltage
Customer	• Industrial • Commercial • Campus • Building	Sub-Transmission or Distribution Systems	Customer Facility	Ensuring customer/local power quality requirements and needs are met
Converter	• Inverter Based Renewables • High-Voltage Direct Current • Medium-Voltage Direct Current	Generation Facility or Transmission System	Transmission or Distribution Systems	Connecting generator electric power output or improving the efficiency of electric power delivery

Table 7. Substation equipment and functions.

Source: Adapted from "Solid State Power Substation Technology Roadmap," (U.S. Department of Energy Office of Electricity, 2020)

Equipment Type	Function	Substation Category
Arresters	Limits the magnitude of voltage transients that can damage equipment by providing a path to ground once a voltage threshold is reached	All
Air-break Switches	Switching device used to reconfigure or isolate parts of the substation to allow for maintenance work	All
Capacitor Banks	Used to increase the voltage at a specific point in the grid and provide power factor correction through reactive power compensation	Transmission, Distribution, Customer
Circuit Breakers	Mechanical switches that automatically isolate circuits in emergency situations to prevent damage caused by excess currents	All
Control House	Provides weather protection and security for control equipment	All
FACTS Devices	Flexible alternating current transmission system (FACTS) alters system parameters to control power flows	Transmission, Distribution
Fault Current Limiters	Limits excessive fault currents in the grid through injection of a large impedance to absorb the energy	Transmission, Distribution
Fuses	One-time safety devices that provide over-current protection by quickly isolating the system during emergency situations	Distribution, Converter, Customer
Power Electronic Converters	Converts AC power to DC power or vice versa	Converter
Instrument Transformers	Measures voltage and current at different points within a substation	All
Reclosers	Device used to detect, interrupt, and clear momentary faults	Distribution
Sectionalizers	Automatically isolates faulted sections of the distribution system	Distribution
Transformers	Step-up or step-down AC voltage levels	All
Protective Relay	Trips a circuit breaker when a fault is detected	All
Voltage Regulators	Maintains feeder voltage levels as loads change throughout the day	Distribution

VII. Bibliography

[1] U.S. White House, "FACT SHEET: President Biden Sets 2030 Greenhouse Gas Pollution Reduction Target Aimed at Creating Good-Paying Union Jobs and Securing U.S. Leadership on Clean Energy Technologies," White House, 22 April 2021. [Online]. Available: https://www.whitehouse.gov/briefing-room/statements-releases/2021/04/22/fact-sheet-president-biden-sets-2030-greenhouse-gas-pollution-reduction-target-aimed-at-creating-good-paying-union-jobs-and-securing-u-s-leadership-on-clean-energy-technologies/. [Accessed 5 October 2021].

[2] P. F. Schewe, The Grid: A Journey Through the Heart of Our Electrified World, National Academies of Sciences Engineering Medicine, 2007.

[3] American Public Power Association, "America's Electricity Generation Capacity 2020 Update," 2020.

[4] T. U. Marston, "The US Electric Power System Infrastructure and Its Vulnerabilities," *Summer Bridge: A Vision for the Future of America's Infrastructure,* vol. 48, no. 2, 2018.

[5] U.S. Department of Energy, "INFOGRAPHIC: Understanding the Grid," U.S. Department of Energy, 17 November 2014. [Online]. Available: https://www.energy.gov/articles/infographic-understanding-grid. [Accessed 19 April 2021].

[6] National Museum of American History, "Origin of Electric Power," Smithsonian Institution, [Online]. Available: https://americanhistory.si.edu/powering/past/prehist.htm. [Accessed 19 May 2021].

[7] J. Susser, "The Evolving Electric Power Grid," advanced energy, 27 February 2020. [Online]. Available: https://www.advancedenergy.org/2020/02/27/the-evolving-electric-power-grid/. [Accessed 19 April 2021].

[8] U.S. Department of Energy, "Grid Modernization Multi-Year Program Plan," U.S. Department of Energy, Washington, D.C., 2015.

[9] Pacific Northwest National Laboratory, "Energy Equity," Pacific Northwest National Laboratory, [Online]. Available: https://www.pnnl.gov/projects/energy-equity. [Accessed 4 October 2021].

[10] U.S. Department of Energy, "Energy Storage Grand Challenge: Energy Storage Market Report," U.S. Department of Energy, Washington, D.C., 2020.

[11] U.S. Department of Energy, "Dynamic Line Rating," U.S. Department of Energy, Washington, D.C., 2019.

[12] Federal Energy Regulatory Commission, "Managing Transmision Line Ratings," Federal Energy Regulatory Commission, Washington, D.C., 2019.

[13] U.S. Department of Energy, "Advanced Transmission Technologies," U.S. Department of Energy, Washington, D.C., 2020.

[14] Federal Energy Regulatory Commission, "RM20-16-000," Federal Energy Regulatory Commission, 19 November 2020. [Online]. Available: https://www.ferc.gov/media/rm20-16-000. [Accessed 2021 June 1].

[15] European Network Transmission System Operators for Electricity, "Dynamic Line Rating (DLR)," European Network Transmission System Operators for Electricity, [Online]. Available: https://www.entsoe.eu/Technopedia/techsheets/dynamic-line-rating-dlr#:~:text=Current%20fields%20of%20research%3A%20Mid,cooling%20effect%20regarding%20wind%20direction. [Accessed 20 April 2021].

[16] S. K. Aivaliotis, "Dynamic Line Ratings for Optimal and Reliable Power Flow," in *FERC Technical Conference*, 2010.

[17] International Renewable Energy Agency, "Dynamic Line Rating Innovation Landscape Brief," International Renewable Energy Agency, Abu Dhabi, 2020.

[18] Johnson, Smith, Young, Donohoo, Owen, Clark, Espejo, Aivaliotis, Stelmak, Mohr, Barba, Gonzalez, Malkin, Dimitrova, Ragsdale, Mitchem, Jeirath, Loomis, Trevino, Syracuse, Hurst, Mereness, Johnson and Bivens, "Dynamic Line Rating Oncor Electric Delivery Smart Grid Program," Oncor Electric Delivery Company Llc, 2013.

[19] PJM, "Report: New Line Technology Boosts Reliability, Reduces Costs," PJM, 14 November 2018. [Online]. Available: https://insidelines.pjm.com/pjm-finds-opportunities-in-new-dynamic-line-rating-technologies/. [Accessed 20 April 2021].

[20] FERC, "Managing Transmission Line Ratings," Federal Energy Regulatory Commission, Washington, D.C., 2019.

[21] Federal Energy Regulatory Commission, "Notice of Workshop," Federal Energy Regulatory Commission, 15 April 2021. [Online]. Available: https://www.ferc.gov/sites/default/files/2021-04/RM20-10-000-workshop.pdf. [Accessed 14 June 2021].

[22] E. B. Fisher, R. P. O'Neill and M. C. Ferris, "Optimal Transmission Switching," *IEEE Transactions on Power Systems,* vol. 23, no. 3, pp. 1346-1355, 2008.

[23] ARPA-E Grid Optimization (GO) Competition, "About the Competition," Advanced Research Project Agency - Energy, U.S. DOE, [Online]. Available: https://gocompetition.energy.gov/about-competition. [Accessed 21 April 2021].

[24] R. A. Kerekes and M. J. Rice, "Seeing double: Digital twin for a secure, resilient grid," Oak Ridge National Laboratory, 11 September 2019. [Online]. Available:

https://www.ornl.gov/blog/seeing-double-digital-twin-secure-resilient-grid. [Accessed 21 April 2021].

[25] Office of Electricity, U.S. DOE, "Transformer Resilience and Advanced Components (TRAC) Program," U.S. Department of Energy, [Online]. Available: https://www.energy.gov/oe/transformer-resilience-and-advanced-components-trac-program. [Accessed 21 April 2021].

[26] A. Burger, "Chattanooga Airport and Partners Plan “Dynamic Boundaries” Microgrid," Microgrid Knowledge, 26 March 2018. [Online]. Available: https://microgridknowledge.com/airport-microgrid-chattanooga/. [Accessed 21 April 2021].

[27] R. Rhodes, "Digital twin technology: Coming to a grid near you," energy central, 17 February 2021. [Online]. Available: https://energycentral.com/o/EPRI/digital-twin-technology-coming-grid-near-you. [Accessed 21 April 2021].

[28] P. A. Ruiz, D. Bowman, K. Dial, X. Li, R. Schoppe, Z. Sharp and B. Tsuchida, "Transmission Topology Optimization," NewGrid Inc., 2018.

[29] Center for Energy Workforce Development, "Gaps in the Energy Workforce 2019 Pipeline Survey Results," Center for Energy Workforce Development, Washington, D.C., 2019.

[30] UC Riverside Online Master of Science in Engineering, "POWER ELECTRONICS AND ELECTRICAL ENGINEERING," UC Riverside, [Online]. Available: https://engineeringonline.ucr.edu/blog/power-electronics-and-engineering/. [Accessed 4 25 2021].

[31] U.S. Department of Energy Office of Electricity, "Transformer Resilience and Advanced Components (TRAC) Program Vision and Framework," U.S. Department of Energy, Washington, D.C., 2020.

[32] PJM, "Basics of Electricity Power Flow on AC Transmission Lines," PJM, 11 July 2013. [Online]. Available: https://www.pjm.com/-/media/training/nerc-certifications/trans-exam-materials/bet/bet-lesson5-power-flow-on-ac-transmission-lines.ashx. [Accessed 14 June 2021].

[33] X. Lou, "The Introduction and Analysis of MTDC System," *Advances in Computer Science Research,* vol. 82, 2017.

[34] A. D. Rosso, E. Ela, S. Uppalapatti, J. Roark, A. Tuohy, L. Trinh and J. Zhui, "Benefits and Value of New Power Flow Controllers," Electric Power Reserach Institute, Palo Alto, CA, 2018.

[35] P. Rodriguez and K. Rouzbehi, "Multi-terminal DC grids: challenges and prospects," *Journal of Modern Power Systems and Clean Energy,* vol. 5, no. 4, p. 515–523, 2017.

[36] U.S. Department of Energy Office of Electricity, "Solid State Power Substation Technology Roadmap," Transformer Resilience and Advanced Components (TRAC) Program, U.S. DOE, Washington, D.C., 2020.

[37] U.S. DOE Advanced Manufacturing Office, "Power America," U.S. DOE, [Online]. Available: https://www.energy.gov/eere/amo/power-america. [Accessed 5 October 2021].

[38] I. C. Kizilyalli , Y. A. Xu, E. P. Carlson, J. Manser and D. W. Cunningham, "Current and future directions in power electronic devices and circuits based on wide band-gap semiconductors," in *IEEE 5th Workshop on Wide Bandgap Power Devices and Applications (WiPDA)*, 2017.

[39] I. C. Kizilyalli, E. P. Carlson and D. W. Cunningham, "Barriers to the Adoption of Wide-Bandgap Semiconductors for Power Electronics," in *2018 IEEE International Electron Devices Meeting (IEDM)*, 2018.

[40] I. C. Kizilyalli and D. W. Cunningham, "Medium Voltage Devices and Circuits Enabling DC Microgrids," in *4th IEEE International Conference on DC Micogrids (ICDCM)*, 2021.

[41] U.S. Department of Energy Office of Electricity, "Modern Distribution Grid Decision Guide Volume III," U.S. Department of Energy, Washington, D.C., 2017.

[42] U.S. Energy Information Administration, "Electricity explained," U.S. Energy Information Administration, 18 March 2021. [Online]. Available: https://www.eia.gov/energyexplained/electricity/electricity-in-the-us-generation-capacity-and-sales.php. [Accessed 19 April 2021].

[43] U.S. Energy Information Administration, "U.S. renewable energy consumption surpasses coal for the first time in over 130 years," U.S. Energy Information Administration, 28 May 2020. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=43895. [Accessed 19 April 2021].

[44] U.S. Energy Information Administration, "Renewables account for most new U.S. electricity generating capacity in 2021," U.S. Energy Information Administration, 11 January 2021. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=46416. [Accessed 19 April 2021].

[45] International Renewable Energy Agency, "Renewables Increasingly Beat Even Cheapest Coal Competitors on Cost," IRENA, 2 June 2020. [Online]. Available: https://www.irena.org/newsroom/pressreleases/2020/Jun/Renewables-Increasingly-Beat-Even-Cheapest-Coal-Competitors-on-Cost#:~:text=Electricity%20costs%20from%20utility%2Dscale,USD%200.115%2FkWh%2C%20respectively.. [Accessed 25 May 2021].

[46] Center for Sustainable Systems, University of Michigan, "U.S. RENEWABLE ENERGY FACTSHEET," University of Michigan, 2020. [Online]. Available:

http://css.umich.edu/factsheets/us-renewable-energy-factsheet. [Accessed 19 April 2021].

[47] Southern California Edison, "Reimagining the Grid," Southern California Edison, 2020.

[48] J. Leisch and J. Cochran, "INTEGRATING VARIABLE RENEWABLE ENERGY INTO THE GRID: KEY ISSUES," Greening the Grid, 2015.

[49] National Renewable Energy Laboratory, "Using Distributed Energy Resources A How-To Guide for Federal Facility Managers," U.S. Department of Energy, Washington, D.C., 2002.

[50] Solar Energy Industries Association, "Principles for the Evolution of Net Energy Metering and Rate Design," Solar Energy Industries Association, May 2017. [Online]. Available: https://www.seia.org/initiatives/principles-evolution-net-energy-metering-and-rate-design. [Accessed 19 April 2021].

[51] B. Kellison, "The next five years will see massive distributed energy resource growth," Wood Mackenzie, 23 June 2020. [Online]. Available: https://www.woodmac.com/news/editorial/der-growth-united-states/. [Accessed May 26 2021].

[52] J. S. John, "'Game-Changer' FERC Order Opens Up Wholesale Grid Markets to Distributed Energy Resources," Greentech Media, 17 September 2020. [Online]. Available: https://www.greentechmedia.com/articles/read/ferc-orders-grid-operators-to-open-wholesale-markets-to-distributed-energy-resources. [Accessed 19 April 2021].

[53] H. K. Trabish, "2021 Outlook: The DER boom continues, driving a 'reimagining' of the distribution system," Utility Dive, 12 January 2021. [Online]. Available: https://www.utilitydive.com/news/2021-outlook-the-der-boom-continues-driving-a-reimagining-of-the-distri/592732/. [Accessed 19 April 2021].

[54] Lawrence Berkeley National Laboratory, "Value of Distributed Energy Resources Largely Depends on Three Things: Location, Location, Location," Lawrence Berkeley National Laboratory, 12 February 2021. [Online]. Available: https://emp.lbl.gov/news/value-distributed-energy-resources-largely. [Accessed 26 May 2021].

[55] SmartGrid.gov, "The Smart Grid," U.S. Department of Energy, [Online]. Available: https://www.smartgrid.gov/the_smart_grid/smart_grid.html. [Accessed 19 April 2021].

[56] DOE Office of Electricity, "Demand Response," Office of Electricity, [Online]. Available: https://www.energy.gov/oe/activities/technology-development/grid-modernization-and-smart-grid/demand-response. [Accessed 15 June 2021].

[57] Environmental and Energy Study Institute, "Beneficial Electrification An Access Clean Energy Savings Program," Environmental and Energy Study Institute, [Online]. Available: https://www.eesi.org/electrification/be#:~:text=Beneficial%20electrification%20(or%20st

rategic%20electrification,the%20residential%20and%20commercial%20sectors. [Accessed 19 April 2021].

[58] M. Muratori, "Impact of uncoordinated plug-in electric vehicle charging on residential power demand," *Nat Energy,* vol. 3, pp. 193-201, 2018.

[59] Pacific Northwest National Laboratory, "Electric Vehicles at Scale – Phase I Analysis: High EV Adoption Impacts on the Western U.S. Power Grid," U.S. Department of Energy Grid Modernization Laboratory Consortium, Washington, D.C., 2020.

[60] M. Alexander, "Plug-in Electric Vehicle Market Projections," Electric Power Research Institute, Palo Alto, CA, 2017.

[61] J. Deason, M. Wei, G. Leventis, S. Smith and L. Schwartz, "Electrification of buildings and industry in the United States Drivers, barriers, prospects, and policy approaches," Lawrence Berkeley National Laboratory, Berkeley, CA, 2018.

[62] J. Gerdes, "So, What Exactly is Building Electrification?," Greentech Media, 5 June 2020. [Online]. Available: https://www.greentechmedia.com/articles/read/so-what-exactly-is-building-electrification. [Accessed 19 April 2021].

[63] T. Gibson, "Engineering Ways to Improve Electrical Grid Resilience," The American Society of Mechanical Engineers, 29 May 2020. [Online]. Available: https://www.asme.org/topics-resources/content/engineering-ways-to-improve-electrical-grid-resilience. [Accessed 19 April 2021].

[64] U.S. Department of Energy, Office of Electricity, "North American Energy Resilience Model," U.S. Department of Energy, Washington, D.C., 2019.

[65] L. Sommer, Interviewee, *A (Load) Balancing Act: The Challenge Of Clean Power.* [Interview]. 18 August 2010.

[66] L. Bird, M. Milligan and D. Lew, "Integrating Variable Renewable Energy: Challenges and Solutions," National Renewable Energy Laboratory, Golden, CO, 2013.

[67] Electric Reliability Council of Texas, "Wind Integration Report," ERCOT, May 2021. [Online]. Available: http://mis.ercot.com/misapp/GetReports.do?reportTypeId=13105&reportTitle=Wind%20Integration%20Reports%20&showHTMLView=&mimicKey. [Accessed 15 June 2021].

[68] EBP US, "Failure to Act Electric Infrastructure Investment Gaps in a Rapidly Changing Environment," American Society of Civil Engineers.

[69] U.S. Department of Energy, "National Electric Transmission Congestion Study," U.S. Department of Energy, Washington, D.C., 2020.

[70] Y. Gu, L. Xie, B. Rollow and B. Hesselbaek, "Congestion-induced Wind Curtailment: Sensitivity Analysis and Case Studies," Texas A&M University, College Station, TX.

[71] U.S. Department of Energy, "Cliamte Change and the Electricity Sector: Guide for Climate Change Resilience Planning," U.S. Department of Energy, Washington, D.C., 2016.

[72] C. Morehouse, "California releases final root cause analysis of August rolling blackouts," Utility Dive, 15 January 2021. [Online]. Available: https://www.utilitydive.com/news/california-releases-final-root-cause-analysis-of-august-rolling-blackouts/593436/. [Accessed 19 April 2021].

[73] L. Doan, "How Many Millions Are Without Power in Texas? It's Impossible to Know for Sure," Time, 17 February 2021. [Online]. Available: https://time.com/5940232/millions-without-power-texas/. [Accessed 19 April 2021].

[74] North American Electric Reliability Coropration, "Special Report Pandemic Preparedness and Operational Assessment: Spring 2020," North American Electric Reliability Coropration, 2020.

[75] U.S. Energy Information Administration, "Cyberattack halts fuel movement on Colonial petroleum pipeline," U.S. Energy Information Administration, 11 May 2021. [Online]. Available: https://www.eia.gov/todayinenergy/detail.php?id=47917. [Accessed 26 May 2021].

[76] D. Shea, "Cybersecurity and the Electric Grid | The state role in protecting critical infrastructure," National Conference of State Legislatures, 24 January 2020. [Online]. Available: https://www.ncsl.org/research/energy/cybersecurity-and-the-electric-grid-the-state-role-in-protecting-critical-infrastructure.aspx. [Accessed 19 April 2021].

[77] Mission Support Center, Idaho National Laboratory, "Cyber Threat and Vulnerability Analysis of the U.S. Electric Sector," Idaho National Laboratory, Idaho Falls, ID, 2016.

[78] U.S. Energy Information Administration, "Annual Electric Power Industry Report, Form EIA-861 detailed data files," U.S. Energy Information Administration, 6 October 2020. [Online]. Available: https://www.eia.gov/electricity/data/eia861/. [Accessed 19 April 2021].

[79] D. Proctor, "Driving Change on the Grid—The Impact of EV Adoption," POWER Magazine, 2 March 2020. [Online]. Available: https://www.powermag.com/driving-change-on-the-grid-the-impact-of-ev-adoption/. [Accessed 19 April 2021].

[80] M. Woodward, D. B. Walton, D. J. Hamilton, G. Alberts, S. Fullerton-Smith, E. Day and J. Ringrow, "Electric Vehicles Setting a course for 2030," Deloitte, 28 July 2020. [Online]. Available: https://www2.deloitte.com/us/en/insights/focus/future-of-mobility/electric-vehicle-trends-2030.html. [Accessed 19 April 2021].

[81] B. Parson, M. Milligan, J. C. Smith, E. DeMeo, B. Oakleaf, K. Wolf, M. Schuerger, R. Zavadil, M. Ahlstrom and D. Y. Nakafuji, "Grid Impacts of Wind Power Variability: Recent Assessments from a Variety of Utilities in the United States," National Renewable Energy Laboratory, Golden, CO, 2006.

[82] ORWG/MWG, Southwest Power Pool, "Dynamic Line Ratings HITT M4 Initiative," Southwest Power Pool, Little Rock, AR, 2020.

[83] A. Taylor, "Use Case Analysis," in *Analysis, Design, and Development Techniques with J2EE*, Pearson, 2002.

[84] J. Taft, E. Stewart and Z. Li, "Extended Grid State Definition Document," U.S. Department of Energy, Grid Modernization Laboratory Consortium, Washington, D.C., 2019.

[85] J. Taft, "Comparative Architecture Analysis: Using Laminar Structure to Unify Multiple Grid Architectures," Pacific Northwest National Laboratory, Richland, WA, 2016.

[86] Advanced Research Projects Agency - Energy, U.S. DOE, "Exploratory Topics," [Online]. Available: https://arpa-e.energy.gov/technologies/exploratory-topics. [Accessed 16 September 2021].