IEEE★USA

IEEE-USA WHITE PAPER

BUILDING AN INTELLIGENT ELECTRIC GRID FOR THE 21ST CENTURY

AN ADDENDUM TO IEEE-USA'S NATIONAL ENERGY POLICY RECOMMENDATIONS

PREPARED BY THE

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This *White Paper: Building an Intelligent Grid for the 21st Century* was prepared by the Energy Policy Committee (EPC) of The Institute of Electrical and Electronics Engineers-United States of America (IEEE-USA), with special assistance from EPC members Harold Adams, Dick Wakefield, Veronika Rabl, Kenneth Lutz, and Thomas Pierpoint. It represents the considered judgment of a group of U.S. IEEE members with expertise in the subject field.

Contents

Introduction

Today's electric grid faces challenges as it transitions to a modern infrastructure that meets our needs in the 21st century. The grid must become more sustainable, resilient, and flexible as well as remaining affordable to all customers. The digitalization of the grid is expected to provide new opportunities for operating the grid with much more situational awareness of grid conditions. In addition, digitalization enables loads to be much more dynamic, responding to grid conditions, rather than simply demanding electric energy. New business models are being created that provide services to new entities, such as load aggregators or demand response services. These new services need to be integrated with the traditional functions of grid operators to instantaneously balance demand and supply to maintain grid reliability. At the same time, new threats are emerging that place additional stresses on the grid operations and lead to new considerations of how we design and plan the build-out of a more intelligent grid. Cybersecurity and extreme weather conditions require new thinking of hardening grid assets and new operational strategies to make the infrastructure inherently resilient.

This paper discusses some of the challenges and considerations for the addressing them. Specifically, it addresses:

- the challenges and opportunities before us and the importance of our timely response to them;
- some considerations of new grid operations and planning that may be required to meet these challenges; and
- key policy and regulatory issues that must be addressed in the short and long terms.

The key drivers for these challenges are the integration of new technologies and the simultaneous emergence of new threat conditions that require new thinking and a new approach toward grid operations and investments. This paper first discusses some of the new technologies that are being introduced into the grid. It then discusses the trends that are providing new opportunities as well as the associated challenges for grid operations. This paper concludes with a set of recommendations for the industry that can assist all participants in the electricity sector.

Some of the new technologies and use alternatives that are being seriously considered, or reconsidered, to meet environmental, economic and reliability goals are described in the following sections of this paper. These include:

- Distributed energy resources (DER)
- Renewable energy resources
- Energy storage systems
- Microgrids
- Plug-In Electric Vehicles (PEVs)
- Demand Response (DR)

- Technologies and system changes required to increase grid resilience
- Transmission additions and upgrades
- Energy efficiency improvements in the electric grid
- Grid system security improvements

As we will discuss, the integration of these alternatives will present system design and operation challenges, and a more intelligent grid (a smart grid) will be required to address these challenges. While the solutions will be unique to each region, Figure 1 shows how some of these smart grid technologies can be integrated in a modernized electric grid.

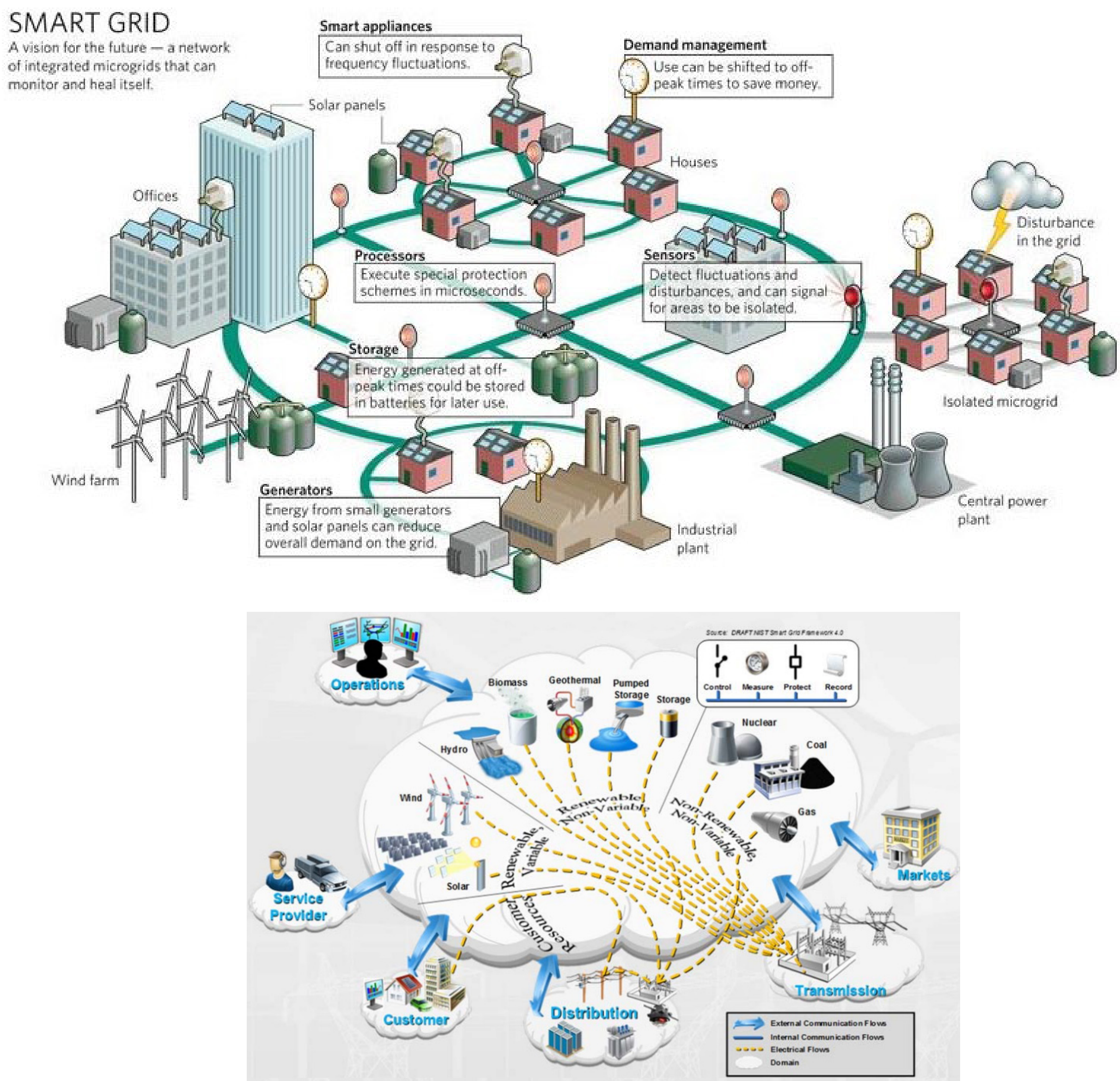

Figure 1: Examples of smart grid technologies that will help modernize the electricity delivery infrastructure

Most of these technologies are already in use to some extent in our regional grids, but judicious increases in their use in various combinations will result in significant economic, environmental and reliability benefits. However, there also will be operational, legal, and regulatory challenges, including:

- More complex grid operation and control
- New information needs, such as system status and dynamic forecasting of future conditions
- Incentives to encourage demand response (DR), renewables, and electric vehicles (PEVs)
- Legal agreements among stakeholders to allow those control actions that are required to protect the overall system and the existing rights of those stakeholders
- Regulatory frameworks that enable innovative solutions to electric grid modernization

Following the sections below on the new technologies and use-alternatives are sections on the associated challenges for grid operations and some near-term actions recommended for all participants in the electricity sector.

Distributed Energy Resources (DER)

Distributed energy resources (DER) are generating facilities that are connected to the distribution grid. The majority of DER units and installed behind the meter and have small power outputs, usually less than 10 or 12 kW [1] . One of the benefits of DER is their potential to provide continued service to nearby loads when outages occur on the higher voltage portions of the regional grid. Another benefit is their ability to produce power to help meet peak demands during periods of high electricity use. In some applications, a portion (or all) of the output of a DER unit may be dedicated to meeting the electrical needs of a specific load or group of loads.

The IEEE-USA developed and delivered reports to the U.S. DOE as part of the White House Quadrennial Energy Review (QER). The IEEE-USA QER report to DOE [2] cites some common impacts of DER on electric distribution grids. Among these are:

- Voltage control issues, including sudden increases and fluctuations, even voltage flicker, that could lead to customer complaints. The increase in voltage fluctuations also pose additional wear and tear on the voltage control (tap changer) devices, thus reducing their effective lifetime.
- Reverse power flows that could cause undesirable interactions with voltage control equipment and system protection system schemes. Computerized protection devices that recognizes power flow direction will have to be updated. (Note that such reverse flows can also pose potentially life-threatening hazards to personnel seeking to restore out-of-service facilities.)

The level at which a distribution circuit can accommodate new DER resources is called "hosting capacity." California, for instance, requires the Investor owned utilities (IOUs) to publish (on the internet) the hosting capacities along distribution circuits. Customers can check for themselves whether or not the hosting capacity of their specific locations has been reached before they apply for installations of rooftop photovoltaic (PV) technologies.

With increasing numbers of DER connecting to the power grid, generation and transmission-owning utilities are faced with a reduction in sales revenues. Furthermore, grid operators are challenged with increasing ramping challenges, particularly for high penetration of solar technology (i.e., duck curve [3]). Distribution utilities are faced with increased distribution costs to accommodate two-way power flows, revised protection schemes, and a more complex voltage regulation system if and when the hosting capacity has been reached. These costs are spread across all customers in most cases, which may raise equity issues. Many states have adopted net metering policies, which turn back the electric meter whenever there is excess power production, implying that the utility compensates the fed-in electricity at the retail rate. These policies have been under review as they do not adequately compensate for the additional investment by the utility to accommodate all feed-in generation.

DER program designs will continue to be challenging for utilities. Increasing numbers of independent companies are actively marketing, selling and installing DER programs to utility end-use customers. The benefits are typically monetized by the independent companies and don't necessarily consider impacts to the utility or the base of other end-use customers.

Renewable Energy Resources

Renewable energy sources include wind power, solar power, hydropower, biomass and geothermal energy, to produce electricity. None of these sources produce significant emissions while generating electricity, and thus, are highly favored by advocates of reduced CO_2 emissions.

The power outputs of wind and solar energy resources vary rapidly with the weather and the time of day. The outputs of hydropower facilities vary more gradually with the seasons of the year and are, therefore, more predictable. Large-scale hydroelectric plants have long been an important energy source in the U.S., and many have already been built on prime locations. Nevertheless, DOE Reports [4] [5] estimates the potential for 65 GW of additional hydropower development in the USA. This is a significant amount, given that DOE-EIA recently reported the total amount of existing conventional hydro capacity in the U.S. to be 79.7 GW [6] producing 6.6% [7] of the total US generation. Canada also has the potential to develop more hydroelectric power plants, and the resulting power could be transmitted to provide electricity services to the US.

Continued increases in wind and solar development is projected for the future for the following reasons:

- Large wind and solar resources in the U.S.
- Falling capital cost for these technologies due to ongoing efficiencies in production and installation efficiencies
- Tax credits at the Federal level and some States

- Preferential treatment by some State Commissions that can take many forms
- Lack of market costs or penalties for variability and intermittency; Solar and wind produce what they can, when they can.
- Free fuel, little labor costs and low maintenance costs
- Increasing price premiums as well as overall revenues that are driven by state and local mandates for renewable energy in many areas of the U.S.
- Various types of legislation, including the renewable portfolio standard (RPS) established by 29 states and the District of Columbia. The current RPS standards and goals for these states and territories are shown in Figure 2.

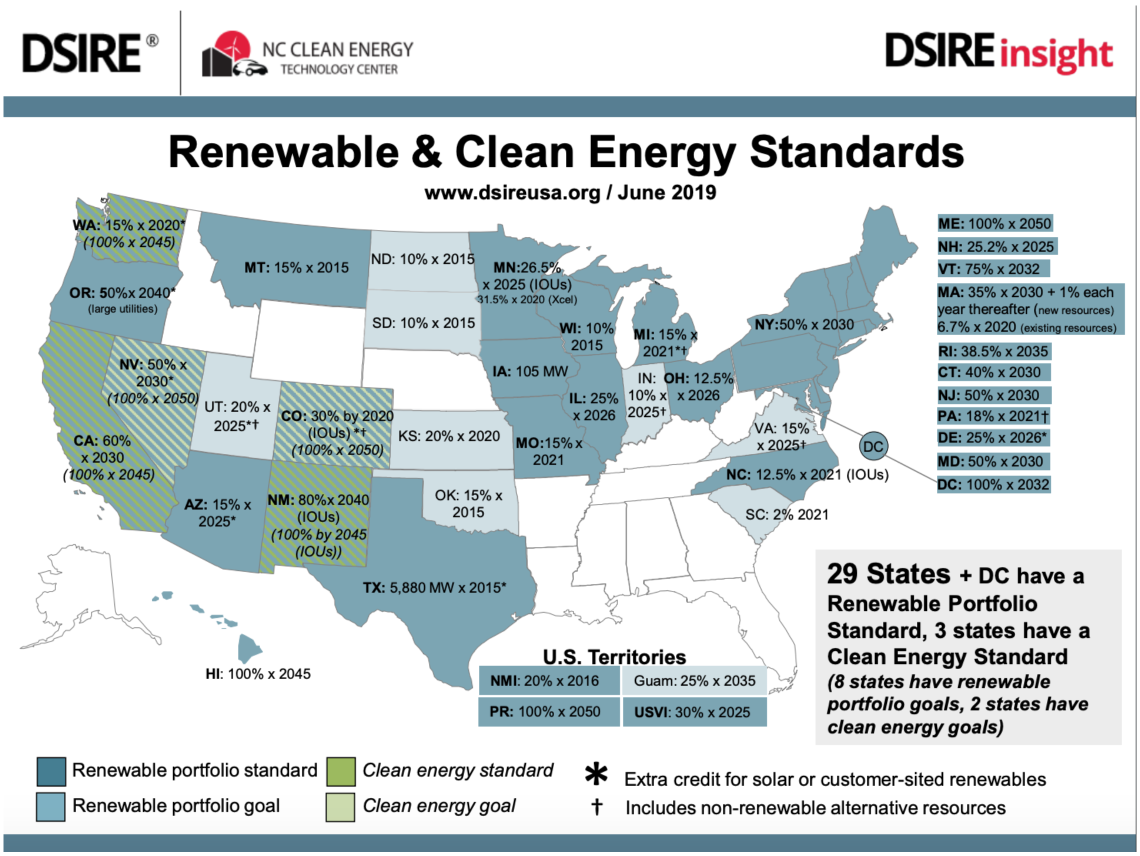

Figure 2: Renewable Portfolio Standards & Goals for U.S. States & Territories - 2019

These factors are expected to drive the following changes in the generation fuels portfolio from the projection period of 2020 to 2050:

- Coal is currently at 24% and is expected to decline to 13%
- Nuclear is currently at 19% and is expected to decline to 12%
- Natural Gas is currently at 37% and this level will remain stable
- Renewable electricity generation is the fastest growing generation resource. The current level is 19% and it is expected to grow to 38%

This is shown in the diagram in Figure 3. [8]

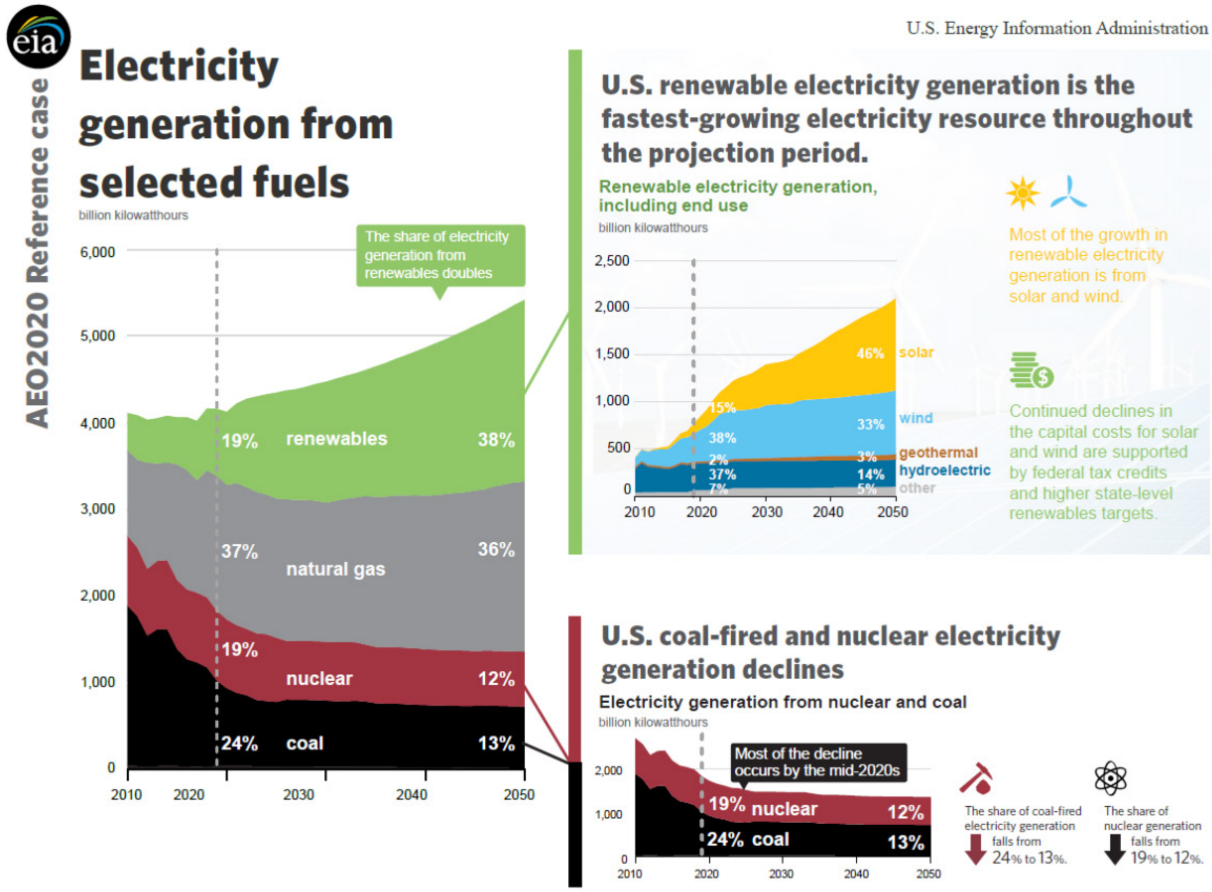

Figure 3: Electricity Generation from selected Fuels – 2020

The grid impacts of adding these renewable energy resources differ between those connected to the transmission (or bulk power) system and those connected to the distribution systems. The comparative impacts of connecting at these two different system levels are discussed below.

Impacts of Connecting at the Transmission Level

There has been major progress in understanding Bulk Power System impacts of connecting renewable energy resources. Recent studies by PJM (and others) have concluded that, "If changes are made to both planning and operational practices, the power system appears to be able to accommodate…high levels of intermittent renewables." [9] However, additional PJM studies report that significant new investments in our transmission infrastructure may be needed to manage large levels of renewables penetration. Also, the State of Minnesota [10] and the Lawrence Berkeley National Laboratory [11] have identified additional detailed studies that "are required for proper planning and operation of the power system." Finally, NREL [12] has identified specific changes in operational practices that will be required. Some examples include:

- Significant penetration of renewable energy resources increases the operating reserve requirements provided via conventional generation and increases the frequency of utilization of these resources.
- Increases in planning reserves can be significant as the firm capacity contributions of both wind and solar photovoltaics (PV) are substantially lower than their nameplate ratings.
- Increasing penetration of renewable energy resources requires greater accuracy and more frequent updating of forecasts of their outputs.
- The mix of generation resources may need to change to provide sufficient flexibility. The renewable energy resources may need controls that can provide frequency response and voltage and frequency ride-through capabilities, as well as ramp control and curtailment, based on system needs. Demand response could be a powerful tool in providing the needed flexibility.

Impacts of Connecting at the Distribution Level

When connected to the distribution system, renewable energy resources present all the same challenges cited earlier for non-renewable DER units. However, the abrupt and rapid output changes caused by the renewable resources' variability may require faster, more costly solutions to these problems.

While the preceding discussion has focused on wind and solar energy sources of renewable energy, most of the same challenges apply (to a lesser degree) to the interconnection of small-scale hydroelectric resources, with outputs that vary diurnally and seasonally with stream flows. Larger-scale hydro is usually treated as a conventional resource, and these plants are usually connected at transmission voltage levels.

Energy Storage Systems

Energy storage systems can help provide power to the grid when it is needed, while allowing electricity to be generated when it is most efficient. Energy storage technologies include various types of batteries, flywheels, pumped hydropower, compressed air, and thermal storage. In the US, pumped hydropower accounts for more electric energy storage than any of the other technologies. In 2018, the total installed capacity of pumped hydropower storage in the US was 22.9 GW.

Energy storage systems have a number of benefits. Energy storage systems can help smooth out the variations of load, which have the effect of reducing the output variations required of intermediate-load generators and peaking plants as they try to keep the grid in balance and of reducing congestion on transmission lines. Such time-shifting also postpones the need for additional generation and transmission capacity and reduces greenhouse-gas emissions from fossil-fuel plants be allowing them to run more efficiently. Energy storage systems can help facilitate the integration of renewable energy resources (solar PV and wind) by smoothing out the inherent variability in their outputs.

Today, the high costs of energy storage are currently limiting its benefit. In its 2014 and 2016 reports to DOE, IEEE states [2], "As penetration levels of intermittent renewables increase, energy storage may become more important for the effective use of…these renewables. However, studies of significant penetration, even at levels of around 30%, do not show energy storage to be essential.

Large-scale energy storage, such as pumped hydro storage, is facilitating the increased use of renewable energy resources. In addition, the use of large-scale energy storage can increase the reliability of electric power supply by providing service continuity for momentary supply interruptions and increasing power quality.

Energy storage can also provide other services. High-power storage systems can be used for frequency regulation more effectively than spinning reserves because of their fast response times. Storage systems also can have an impact in reducing energy prices through arbitrage in the markets. On the customer-side of the meter, energy storage can: 1) provide back-up power to increase customer service reliability; 2) help to integrate distributed generation directly; and 3) reduce customer costs through arbitrage.

Some of the challenges facing energy storage include high costs, which are coming down over time; regulatory hurdles because storage systems act as both generators and loads; and a need for more models and experience to indicate best locations, sizes, and types of energy storage systems.

Microgrids

Microgrids are small electric grids that have their own defined loads and sources of generation. They may either be embedded within a larger utility grid or connected to a utility grid with interchange arrangements. More precisely, IEEE's QER Report [2] states, "A microgrid is defined by four qualities: it manages a group of interconnected loads, it uses DG [distributed generation], it has a clearly defined electrical boundary between it and any other power system, and it has the ability to island and support load on its own."

Microgrids include a number of components, typically including generation, distribution, loads, energy storage, and operational monitoring and control systems. The current growth in microgrids is occurring among large utility customers, including military installations, the commercial shipping and ports industry, hospitals, and universities. Recent, renewed interest in microgrids has been driven by lower-cost renewable generation, improvements in energy storage technologies, automated demand response, and lower natural gas prices.

As the traditional servers of the large customer loads, electric utilities have concerns about the movement toward microgrids. These concerns are driven by the associated losses in sales and annual revenues and, to a lesser degree, the increased complexity of system operations. In response to these concerns, IEEE observes that, "Utility concerns over revenue could be allayed if utilities developed a positive business case for implementing their own microgrids and optimally integrating non-utility microgrids, while obtaining regulatory rewards for quantifiable customer benefits unrelated to infrastructure investment and volumetric electricity sales" [2]. If utilities address microgrids in this way, it could lead to a future-oriented business model, with benefits for all stakeholders.

It is clear that the trend towards building microgrids for certain large customers is likely to continue with recent technology developments, including renewable energy resources, energy storage, and smart grid applications. As a result, there is a compelling need for the participation and support of local, state, and federal regulators and research agencies. Some of the issues they can help to resolve include:

- Development of interconnection standards and cost responsibilities;
- Equitable charging arrangements for back-up supply from the incumbent utility; and
- Active encouragement of the utilities' pro-active involvement in implementing and integrating microgrids.

Plug-In Electric Vehicles

If current trends continue, the rapidly growing adoption and use of Plug-In Electric Vehicles (PEVs) will have a major impact in reducing our nation's use of oil for transportation and will significantly reduce harmful air emissions in our cities and towns. [13] In 2018, transportation accounted for approximately 70% of total U.S. petroleum use [14] and for 30% of the country's greenhouse gas (GHG) emissions [15]. Also, as Figure 4 shows, recent EPA statistics indicate that light duty vehicles (automobiles and small trucks) were responsible for well over half of all GHG emissions by the US transportation sector in 2018. [16]

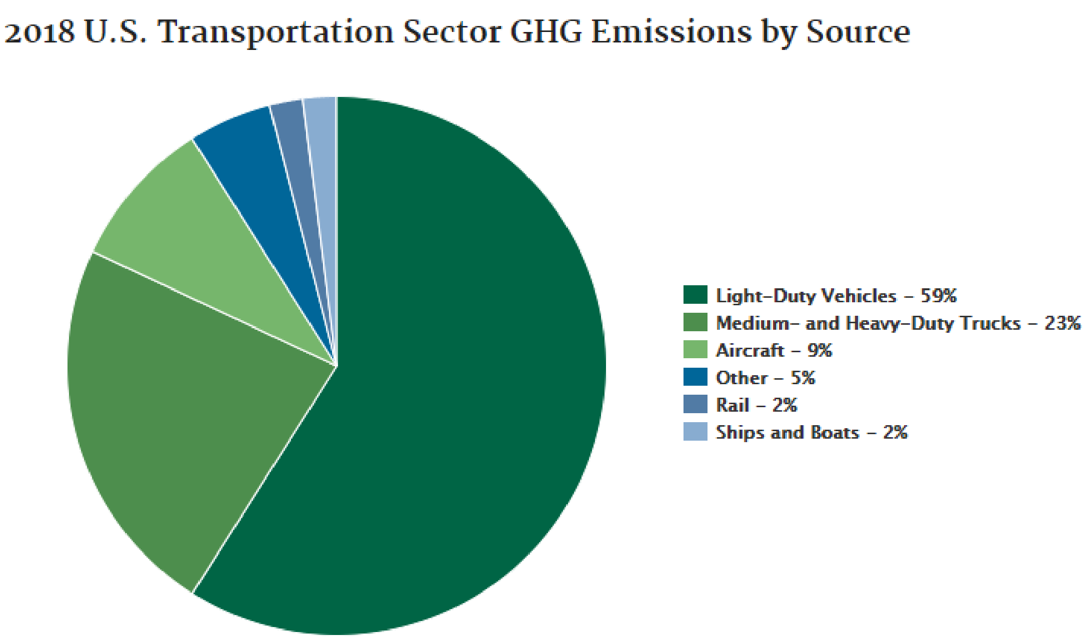

Figure 4: LDVs Responsible for Most GHG Emissions.

Significant transportation energy efficiency gains also are likely from increases in the use of PEVs. While conventionally powered automobiles and small trucks have fuel efficiencies of approximately 12%, PEVs have fuel efficiencies of 19% to 32% (for coal-based electricity) and 27% to 42% (for natural gas-based electricity) [13].

There is clear support among U.S. electric utilities for a steady growth in the use of plug-in electric vehicles. This support stems from 1) the attractive electricity sales and revenue increases that will result and 2) the likelihood that many will be charged during off-peak hours, thus boosting utility load factors. Also, in many instances PEV charging can take place over longer time periods than required for a fast recharge. This offers the potential for interruptions in the charging load or even brief vehicle-to-grid power flows.

Obviously, significant changes to the U.S. grid will be required to accommodate a large-scale adoption of PEVs. However, because the change is taking place over 10-20 years, its effects are predictable and can be managed. In its QER Report to DOE [2], IEEE discusses the transmission and distribution system changes that will be required in some detail and concludes that:

- The transmission system should be able to handle the load from between 8 and 12 million PEVs without any major upgrades. This assumes a reasonably even distribution of PEVs around the United States. Should most or all of the PEVs cluster in a single region, they may change the demand enough to create the need for additional transmission capability [17]; and
- Distribution system impacts will be significant as the numbers of PEVs grow; however, distribution planners have technical solutions to expand the grid just as they provide for new housing developments.

As further evidence that the utility industry supports a movement to adopt PEVs, Electric Power Research Institute (EPRI) reports [18] that, "…a consortium of eight automakers and 15 electricity utilities has been formed to address the PEV interface with the grid." PEVs, through their energy storage systems, can provide important "electric services to the grid [through] 'vehicle-to-grid'" integration [19]. All of the PEVs in a distribution grid can, through advanced control technologies, act as a single energy storage system to provide important services such as frequency regulation to stabilize generation output fluctuations. Some possible measures to promote electric vehicle adoption have been suggested by IEEE Life Fellow, Dr. James Gover, including [20]:

- Rebates for (PEV) purchases;
- Special driving lanes and parking privileges;
- Adopting higher CAFE standards for all vehicles;
- Purchasing PEVs for government uses;
- Providing better information on the costs and benefits of PEVs; and
- Offering funding for PEV R&D and (public) education.

Demand Response

Demand response (DR) is an important resource that "offers significant potential economic and reliability benefits, including peak load reductions, improved system efficiency and flexibility, enhanced reliability, and avoided investments in new transmission and generation capacity." A typical definition of DR is "…an umbrella term that encompasses a variety of arrangements under which consumers (i.e. the demand side of the power market) intentionally reduce or increase (or agree to an adjustment of) their consumption of electricity in response to price signals or power grid needs" [21].

DR resources play an increasingly important role in ensuring the reliable and cost-effective availability of electricity and can be as helpful as generation of additional supply in maintaining the reliability of the grid. DR may, in fact, offer advantages over generation under certain circumstances, such as drawing upon them at peak times to reduce the overall cost of electricity. There are four points to understand about the function of the electric grid and the role of DR resources [22]:

1. The physical properties of electricity require grid operators to instantaneously and continuously balance the "generation" (i.e., supply) of electricity with "load" (i.e., demand).
2. As grid operators balance generation and load on the grid, using DR resources can, in many instances, fulfill the same purpose as purchasing additional generation resources.
3. DR resources can in some circumstances provide advantages over generation resources in facilitating grid operators' mission of maintaining a reliable flow of electricity. Not only do DR resources provide an additional flexible tool, but because they can be quickly activated— including in specific locations, where needed—they can substantially help to achieve balance on the grid and thus avoid service disruptions.
4. DR resources directly affect prices in the wholesale energy and ancillary services markets. The algorithms that grid operators use to collect bids on and dispatch electricity look for the lowest price available (given reliability constraints). At times, the price of purchasing DR will be lower than the price of purchasing additional generation. Moreover, the economics of the energy market cannot be disconnected from the reliability factors involved in balancing the grid and maintaining reliable operation of the grid. The pricing system takes into account reliability factors, so that grid operations and energy markets (including their reliance on DR resources) are inherently intertwined with each other. Also, by reducing demand on the grid, DR resources can potentially lessen the need for additional transmission system upgrades, providing further cost efficiencies.

Demand Response includes both Retail DR and Wholesale DR. Retail DR is procured and under the control of Utilities. Wholesale DR is procured in organized markets for each balancing authority [23] .

Since 2006, FERC has published annual reports on the contribution of Demand Response resources and advanced metering required by section 1252(e)(3) of the Energy Policy Act of 2005 (EPAct 2005) [24]. The latest report indicates that:

- Retail DR demand savings were 31,508MW. Figure 5 shows Retail DR Peak Demand Savings by Region and Customer Class.
- Wholesale DR demand savings were 27,541MW in 2017 and 29,674MW in 2018. Figure 6 shows the wholesale DR by Region.

Region	Customer Class				
	Residential	Commercial	Industrial	Transportation	All Classes
Alaska	5.0	13.0	9.0	0.0	27.0
FRCC	1,500.7	1,335.7	276.0	0.0	3,112.4
Hawaii	14.2	18.4	0.0	0.0	32.6
MRO	2,158.1	1,103.2	2,098.4	5.0	5,364.5
NPCC	120.1	385.1	316.3	0.0	821.4
ReliabilityFirst	1,658.2	907.7	3,605.2	0.0	6,171.0
SERC	1,617.2	805.2	6,365.5	0.0	8,787.9
SPP RE	280.9	966.6	453.0	0.0	1,700.4
Texas RE	238.1	376.0	209.8	0.0	823.8
WECC	1,351.0	1,084.3	2,118.5	0.0	4,553.7
Unspecified	52.5	0.0	60.3	0.0	112.8
All Regions	**8,996**	**6,995**	**15,512**	**5**	**31,508**

Sources: EIA, EIA-861 Demand_Response_2017 and Utility_Data_2017 data files.

Note: Although some entities may operate in more than one NERC region, EIA data have only one NERC region designation per entity. Commission staff has not independently verified the accuracy of EIA data.

Figure 5: Potential Peak Demand Savings (MW) from Retail Demand Response Programs (2017)

RTO/ISO	2017		2018		Year-on-Year Change	
	Demand Resources (MW)	Percent of Peak Demand [8]	Demand Resources (MW)	Percent of Peak Demand [8]	MW	Percent
CAISO	1,293 [1]	2.6%	2,400 [9]	5.2%	1,107	85.6%
ERCOT	3,009 [2]	4.3%	3,262 [10]	4.4%	253	8.4%
ISO-NE	684 [3]	2.9%	356 [11]	1.4%	-328	-48.0%
MISO	11,682 [4]	9.7%	12,931 [12]	10.6%	1,249	10.7%
NYISO	1,353 [5]	4.6%	1,431 [13]	4.5%	78	5.8%
PJM	9,520 [6]	6.7%	9,294 [14]	6.3%	-226	-2.4%
SPP	0 [7]	0.0%	0 [7]	0.0%	0	0.0%
Total	**27,541**	**5.6%**	**29,674**	**6.0%**	**2,133**	**7.7%**

Figure 6: Wholesale Demand Response Participation in RTOs/ISOs (2017 & 2018)

The annual FERC reports also indicate the following:

- There has been a multi-year decline of Retail DR (Utility controlled) across most parts of the U.S.
- There has been a multi-year increase in the level of Wholesale DR (Market controlled) across most parts of the U.S.
- The regulatory agencies are different for Retail DR versus Wholesale DR.
- For Retail DR, the FERC report probably understates the role of the 50 State Commissions (plus Washington DC). It also does not mention US Territories which are becoming increasingly relevant, especially Puerto Rico.

These are all factors to consider in the designs of DR programs. There is strong support in the power industry for continued growth in the use of demand response because of its proven economic and reliability benefits. Specifically, the Bipartisan Policy Center has stated its support for "…policies that will encourage the further active participation of demand-side resources in electricity markets" and has further recommended that "Market operators and regulators should permit demand response resources, including demand response aggregators, that are capable of performing in a manner comparable to conventional generation to participate in electricity markets and auctions on the same terms as generation resources" [21].

Technologies and System Changes Required to Increase Grid Resilience

All of the technologies addressed in the previous six sections can contribute to building a more resilient electricity grid. As defined in Presidential Policy Directive 21, the term "resilience" refers to "…the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions. Resilience includes the ability to withstand and recover from deliberate attacks, accidents, or naturally occurring threats or incidents." [25]

The U.S. Department of Energy (DOE) has recently stated that it is "… adopting a public/private partnership approach to join with key stakeholders in developing and implementing a resilient grid R&D plan." [25] As part of this initiative, the "DOE Smart Grid R&D Program has launched a national effort on electric distribution grid resilience." The program has the objectives of:

- "modernizing the electric distribution grid through the adoption and integration of advanced technologies (information, communications, and automation) and new operational paradigms (microgrids and transactive controls);
- "supporting the increasing demand for renewable energy integration and grid reliability and resiliency at state and local levels."

DOE R&D efforts are focused on increasing the U.S. grid's resilience to "climate change and extreme weather events." This focus results from the observation that, "…the frequency and intensity of these disaster events have been trending higher in recent years." [25] While Climate Change remains an area of intense debate among many, the impacts of severe weather and climate disasters are documented and hard to deny.

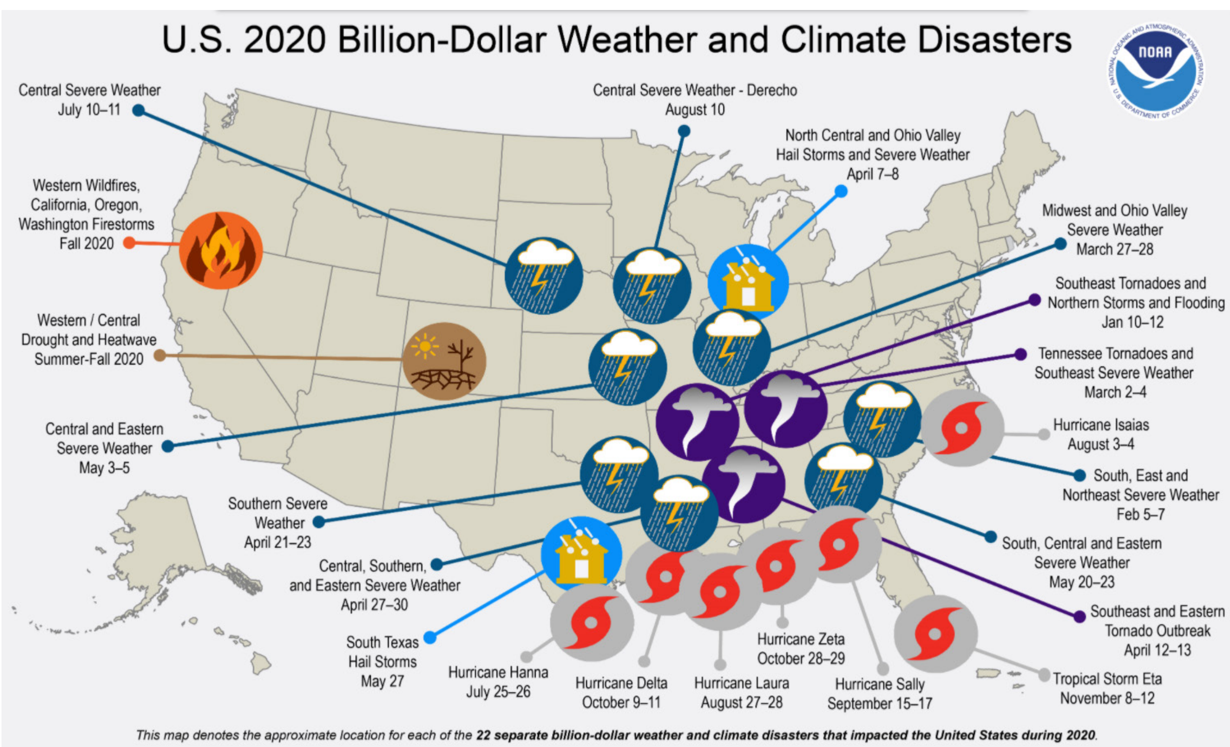

Figure 7: The Locations of fourteen US$1 Billion Weather and Climate Disasters in 2020

Since 1980, the U.S. has sustained 285 weather and climate disasters, where each event reached or exceeded $1B. The total cost is $1.875 Trillion for these 285 billion-dollar events. Figure 7 shows 2020, which sets the new annual record of 22 events — shattering the previous annual record of 16 events that occurred in 2011 and 2017. Furthermore, 2020 is the sixth consecutive year (2015-2020) in which 10 or more billion-dollar severe weather and climate disaster events have impacted the United States. The years with 10 or more separate billion-dollar disaster events include 1998, 2008, 2011-2012, and 2015-2020. [26]

Based on input from stakeholders, the DOE Smart Grid R&D Program has identified five needs for resilient distribution grid R&D [25], including:

- Develop resilience metrics;
- Enhance system design for resiliency;
- Improve preparedness and mitigation measures;
- Improve system response and recovery; and
- Analyze and manage interdependencies.

For example, increased resilience might result in redesigning portions of the distribution grid from a lower-cost radial system to a networked system. Each of the above-listed needs is discussed further in a DOE article in *IEEE Power & Energy Magazine* [25].

While most of this discussion has focused on increasing the resilience of our distribution systems, there also are concerns about the future challenges to the resilience of our bulk power (transmission) grids. Many of these challenges stem from concerns about our increasing reliance on renewable energy resources, such as wind and solar generation, with often rapidly varying output levels that are difficult to predict. Rapid reductions in the regional outputs of these generation sources could require system operators to take “under-frequency actions,” i.e. load-shedding, to maintain acceptable frequency levels on the regional system(s) to which they are connected.[1]

At the present time, many renewable energy resources, such as wind and solar generators, do not have the same automatic control systems that conventional generators have to adjust their outputs when frequency deviations occur. However, such automatic controls are now technically feasible, and numerous industry organizations, such as NERC (North American Electric Reliability Corporation), NARUC (National Association of Regulatory Utility Commissioners), and UWIG (Utility

1 Within the electric power system, frequency must be kept within standardized limits by maintaining a close balance between total system generation and total system load (including losses). In simple terms, when the total system load at any time exceeds the amount of power being generated, the frequency will decrease below the nominal standard. Similarly, when the amount of power being generated exceeds the total system load (including losses), the frequency will increase above the nominal standard. Most conventional generators include automatic controls that respond to frequency changes by increasing or decreasing their power output levels to compensate. System operating centers also play a key role by re-dispatching generating sources under their control to meet anticipated increases or decreases in the system loads those sources must serve. However, industry data has shown that increased attention needs to be given by all generators to maintaining proper frequency control to help further stabilize the grid.

Wind Interest Group), support actions by the generation owners and system operators to require that primary frequency response be provided by all renewable energy resources connected to our regional power systems [27].

System resilience addresses a different class of outages from system reliability. In his recent IEEE publication, Dr. Chen-Ching Liu [28, pp. 93-96] distinguished between our current reliability indices, which are based on typical outages, and metrics that are needed for catastrophic outages, such as those that result from the weather and climate disasters identified in Figure 8. Dr. Liu's differentiation, shown in Figure 8, highlights the differences between these two outage classes. He stated, "The resiliency of a distribution system is defined with respect to a system's ability to withstand rare and extreme events. … numerous components may be damaged, power sources may become unavailable, and transmission/distribution system facilities may not be ready for service restoration…. As a result, by existing reliability metrics, a highly reliable distribution system is not necessarily resilient."

Typical Outages	Catastrophic Outages
Most cases involve a single fault or failure.	Multiple components are damaged.
A small number of customers are affected.	A large number of customers are affected.
Power sources are available and accessible.	Power sources may not be available and accessible.
Transmission and distribution system facilities are available.	Transmission and distribution system facilities may be damaged or unavailable.
Repair and restoration are straightforward.	Repair and restoration are complex.

Figure 8: Typical and Catastrophic Outages

Transmission Additions and Upgrades

Many changes to our regional transmission systems will be required as a direct result of:

- Delivering power from distant renewable energy resources and
- Closing many large coal plants to reduce CO2 emissions and improve air quality.

The most economic locations for large-scale wind and solar generation are often many miles away from major load centers; therefore, new transmission facilities may be needed to deliver the power they produce. Such transmission facilities are costly and time-consuming to construct, and they also require inter-state and inter-regional planning and cooperation to complete.

EPA's mandated reductions in CO_2 emissions will also require new and upgraded transmission facilities. As many of the existing coal plants close, they will have to be replaced with new generation. A significant fraction of these new generation plants will be in different locations from the coal plants and will therefore be interconnected to the transmission system at different locations. This will result in changed power-flow patterns on our regional transmission systems, and new facilities will be needed in most regions.

Most of our regional grids in the U.S. continue to rely primarily on High Voltage Alternating Current (HVAC) transmission facilities. In the future, the challenges posed by some of the changes to the generation system discussed here may be best served by High Voltage Direct Current (HVDC) facilities. For example, the delivery of large amounts of wind power from western regions to eastern load centers may be accomplished more efficiently by HVDC lines dedicated to that purpose. Power transfers on HVDC lines can be scheduled, and the line losses are significantly lower than those on comparably-sized HVAC lines. HVDC has also been extensively used to 1) enable power transfers between neighboring grids, such as the eastern and western interconnections and 2) facilitate and schedule long-distance transmission of bulk power from abundant, low-cost sources. Some examples include:

- Hydro-Quebec's interties into the New England Power Pool (NEPOOL);
- The Pacific Northwest/Southwest intertie on the Western Interconnection (WECC);
- The Cross-Sound HVDC cable between Connecticut (NEPOOL) and Long Island (NYPP); and
- The NEPTUNE cable between New Jersey (PJM) and Long-Island (NYPP).

In summary, HVDC can be an excellent solution when transmission is being built for very specific power deliveries between established grids with different operators.

Our aging transmission infrastructure will require many replacements and upgrades in the near future. All of these transmission additions and upgrades will be planned and coordinated by the Regional Transmission Operators (RTOs), established by FERC, and by the transmission-owning utilities. In most cases, state and local regulatory bodies will review and approve the associated facilities' needs, sitings, and costs. Although these upgrades take time to complete, many of them are already at various stages in the pipeline. An example of one region's transmission expansion plans, those of the Midwest Independent System Operator (MISO), can be found on its website at: https://www.misoenergy.org/Planning/TransmissionExpansionPlanning/Pages/MTEP13InfoGraphic.aspx

Energy Efficiency Improvements in the Electric Grid

Some energy is lost on the electric transmission and distribution (T&D) system as it is delivered from power generators to consumers, with losses in the US typically estimated to be about 5-7%. These losses represent an annual cost to consumers of between $20 - $28 billion on overall U.S. electric sales of $402 billion. [29] The level of these losses varies somewhat across the U.S. depending upon the design characteristics of the electrical grid in each state.

Reducing T&D losses means a reduction the total amount of generation required to serve a given amount of customer load at any time. For example, reducing T&D losses by 10 MW would also reduce the required generation output needed by 10 MW. This in turn reduces consumption of fuel by the generators and eliminates the related CO_2 and other emissions. Since output of most renewable energy sources and nuclear plants is not dispatchable,[2] reducing losses nearly always reduces fossil fuel generation; however, achieving this energy savings in operations may require additional equipment investment up front.

There is usually an economic trade-off between loss reduction and capital cost, but the mechanism for capital-cost recovery through electric rates varies. The cost of lost and other unaccounted for energy is generally borne by customers, which they see in their electric bills as an embedded part of a fuel factor charge (often called a Power Supply Cost Recovery charge or credit) or some other rate mechanism. Capital costs for T&D equipment are also borne by customers through regulated rates for T&D delivery service.

While losses cannot be entirely eliminated, they can certainly be controlled. Decisions about which existing and new grid technologies to employ are often made by Regional Transmission Operators and can have an impact on the overall level of system energy losses and environmental impacts. Therefore, losses must be explicitly considered at both the local and regional level when making technical, economic, environmental, and regulatory decisions concerning the development of the grid. Power system losses are generally minimized when:

1. Power is generated close to the load (distributed generation).
2. Higher voltage lines and equipment are used.
3. Losses are considered in the economic evaluation of T&D equipment purchases and related technical standards for equipment.
4. The configuration of the network is properly designed for the amount and nature of loads to be served, including:
    a. Properly sized equipment,
    b. Appropriately sized wires, and
    c. Optimized voltage controls.
5. Round-trip efficiency of any deployed energy storage system is high.

The deployment of new technologies, such as distributed energy resources, microgrids, and energy storage systems, is likely to reduce losses and increase the efficiency of the T&D grid. For example, distributed energy resources are always close to the loads, thereby avoiding large transmission losses. Demand response to minimize peaks also reduces losses by reducing current flows on the system when the load is peaking. Microgrid control systems can increase the efficiency of

2 Dispatchable generation refers to sources of electricity that can be dispatched at the request of power grid operators or of the plant owner; that is, generating plants that can be turned on or off, or can adjust their power output accordingly to an order. Most dispatchable generation is fossil fueled or hydro.

their distribution systems. New types of batteries, located closer to loads, are likely to have superior efficiency compared to large pumped storage hydro power plants.

Grid System Security Improvements

In addressing power system security, IEEE's report to DOE for use in its QER [2] specifically discusses the growing challenges of maintaining or improving the physical and cyber security of our electric grid assets. This section reviews some of the recommendations.

The concept of asset management extends to the physical and cyber security of those assets, which introduces new challenges:

- Physical security – The size and complexity of the North American electric power grid makes it impossible both financially and logistically to physically protect the entire end-to-end and interdependent infrastructure.
- Cyber security – Threats from cyberspace to our electrical grid are rapidly increasing and evolving. Public disclosures of grid vulnerabilities are making it more attractive as a target.

The critical elements of our transmission and distribution systems that need to be protected include: transmission lines (especially those linking areas of the grid), key substations and switchyards, control centers, and distribution grids of national significance. The last category would include, for instance, feeders to major urban areas or facilities that have national impact.

The following possible strategies are among those that have been discussed by power industry organizations including IEEE, Edison Electric Institute (EEI), NERC and the Electric Power Research Institute (EPRI). These strategies address key transmission, distribution, control and communications system challenges and recommended actions, including the following:

- Transmission Lines
  - Physical security is not possible because there are too many transmission lines out in the open. We need to address this vulnerability either through redundancy or through mitigation strategies.
  - Redundancy can be improved by expediting the siting of needed transmission lines.
  - The use of safe, energized work techniques (e.g. using robotic technologies) to maintain, repair, re-conduct, and rebuild lines and equipment is one of the solutions to reduce congestion and associated costs and minimize service interruptions [30].
  - Further R&D is needed across the industry to create appropriate alarms, e.g., using information from transducers used for line sag/temperature/etc. might elucidate improved alarming opportunities.
- Key Substations & Switchyards

  - Although physical security is possible, the correct level of security needs to be determined via a triage process under which utilities protect their most valuable resources first.
  - Since recovery from an attack is impeded by the long lead-time required to obtain transformers and other components, they need to be stockpiled to make them more readily available.
  - Continue to implement spare equipment programs and initiatives, such as EEI's Spare Transformer Equipment Program (STEP) and NERC spare equipment initiatives.
  - Continue to work with industry and manufacturers to expand the existing self-healing transformer and grid programs and to standardize and modularize key equipment to make replacement easier. Such efforts are now underway by EPRI and ABB.
- Distribution Grids of National Significance
  - Grid redesign should be considered to make the distribution system less radial and more interconnected for the re-routing of power around outages.
- Controls & Communications
  - Outreach and awareness by the industry for the development of standard requirements, e.g., for control system personnel, procedures, and technology.
  - The industry should promote and facilitate communications and cyber security audits, redundancies, and back-up systems.

These and other recommendations for increased grid security are discussed further in IEEE's Quadrennial Energy Report [2].

Conclusions

The U.S. electric power grid faces major challenges in 1) integrating abundant, but often distant, renewable generation sources, 2) reducing the harmful emissions from conventional generating plants, and 3) increasing the resilience of its current power delivery systems in the face of increasingly severe weather events attributed to climate change. This paper discusses these challenges and some possible solutions. Many related actions have already been initiated, but more are needed to accelerate the needed changes to our grid.

The following actions should be actively supported and encouraged by all participants in the electricity sector.

1. Significantly increasing the transmission capacity from remote wind and solar sites to major load centers;
2. Active encouragement for utility feed-in tariffs that fairly compensate owners of solar and wind facilities at customer sites;
3. Review and reform of retail rate structures to help optimize deployment of solar and battery technologies, with the goal being to compensate the solar and battery owner for services provided, given the locational and temporal value of their devices;
4. Increasing the abilities of customers to lease on-site solar PV systems;
5. Continued incentives for plug-in electric vehicle (PEV) purchases.
6. Industry funding for electric vehicle R&D and for public education;
7. Full cooperation from local utilities in connecting to, and interchanging with, microgrids, under terms that fairly compensate both parties; and
8. Modification of rate structures to encourage and compensate customers fairly for participation in demand response activities and programs.
9. Utility actions to fully evaluate the resilience of their respective transmission and distribution systems and to develop plans to increase that resilience, where needed. Such plans should consider needed changes in both system design and operation.
10. Increased efforts by all types of generators to maintain proper frequency controls as an effective means of further stabilizing the grid.
11. Establish a workforce for the 21st century intelligent grid. This workforce will be planning the built-out of the grid as well as operating the future grid with more situational awareness and use of a large spectrum of bulk power and distributed resources.

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