GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

Emerging Trends and Systemic Issues Influencing Today's U.S. Electric Grid

Context for Grid Architecture Development

Yaosuo (Sonny) Xue, ORNL
Guodong Liu, ORNL
Jeffrey D. Taft, PNNL
Mallikarjun (Arjun) Shankar, ORNL

GMLC-1.2.1

Emerging Trends and Systemic Issues Influencing Today's U.S. Electric Grid

Context for Grid Architecture Development

Yaosuo Xue, Oak Ridge National Laboratory
Guodong Liu, Oak Ridge National Laboratory
Jeffrey D. Taft, Pacific Northwest National Laboratory
Mallikarjun (Arjun) Shankar, Oak Ridge National Laboratory

February 2022

ORNL/TM-2022/2372

Oak Ridge National Laboratory

Emerging Trends and Systemic Issues Influencing Today's U.S. Electric Grid

Yaosuo (Sonny) Xue, ORNL
Guodong Liu, ORNL
Jeffrey D. Taft, PNNL
Mallikarjun (Arjun) Shankar, ORNL

February 2022

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

DOCUMENT AVAILABILITY

Reports produced after January 1, 1996, are generally available free via US Department of Energy (DOE) SciTech Connect.

Website www.osti.gov

Reports produced before January 1, 1996, may be purchased by members of the public from the following source:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone 703-605-6000 (1-800-553-6847)
TDD 703-487-4639
Fax 703-605-6900
E-mail info@ntis.gov
Website http://classic.ntis.gov/

Reports are available to DOE employees, DOE contractors, Energy Technology Data Exchange representatives, and International Nuclear Information System representatives from the following source:

Office of Scientific and Technical Information
PO Box 62
Oak Ridge, TN 37831
Telephone 865-576-8401
Fax 865-576-5728
E-mail reports@osti.gov
Website http://www.osti.gov/contact.html

ORNL/TM-2022/2372

Electrical & Electronics Systems Research Division
The Center for Computational Sciences

Emerging Trends and Systemic Influencing Today's U.S. Electric Grid

Author(s)

Y. Xue
G. Liu
J. Taft
M. Shankar

Date Published:

February 2022

Prepared by
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, TN 37831-6283
managed by
UT-BATTELLE, LLC
for the
US DEPARTMENT OF ENERGY
under contract DE-AC05-00OR22725

Executive Summary

With increasing shifts from vertically integrated to horizontally structured operations and from centralized to distributed electric power delivery, today's electric power grid (the "grid") operators and designers face the challenge of creating an architecture that accommodates a host of diverse requirements. The grid's modes of operation must address concerns of reliability and stability, new deployments of renewable energy sources, threats from cyber-attacks and natural disasters, and increasingly distributed system operations. Grid modernization calls for a reliable, affordable, sustainable, agile, secure, and resilient grid. However, the modernization of the U.S. power grid is hampered by mounting complexity and diverging objectives from owners and operators and is consequently risky and fraught with potential missteps. Flawed architecture, design, and implementation will lead to stranded investments and lost opportunities. A principled approach to minimize risk and develop a robust grid of the future is to begin with a sound architecture for the grid to inform the design process. Architecture development starts with the context of influencing factors that provide constraints as well as driving goals. This report provides the context of emerging trends and cross-cutting systemic issues in the U.S. electric power grid and serves as a vital input for grid architecture development.

After a brief introduction, the first part of the document (Section 2) presents a listing of emerging trends, which are factors that are typically exogenous but on occasion endogenous to the grid today. Here, we define the emerging trends as those drivers that create challenges, opportunities, and influence future directions in the evolution of the grid. These could be technology, policy, or societally driven and cause the grid to evolve and adapt if and where necessary. The emerging trends are organized by vertical categories including generation, load, control, data and communications, operation and planning, business and markets, and grid properties attracting increasing worldwide attention, including resilience, physical and cyber security, and decarbonization. There has been continuous network convergence and growing dependence among gas, heat, electricity, building, transportation and information and communication technology (ICT) systems. With increasing penetration of distributed energy resources, grid-interactive efficient buildings (GEBs), demand response, smart edge-devices, as well as microgrids – components emerging as the fundamental building blocks of the electricity delivery system - today's electric grid needs to transform itself into a more distributed and flexible structure in a socially equitable and secure manner.

The second part (Section 3) of this document presents a listing of the cross-cutting systemic issues, which are structural and run-time considerations of grid operations that are extant in the grid and deserve to be addressed to support new requirements and objectives. We define systemic issues as those inherent in the overall system that create challenges in design and operation that need to be solved. Systemic issues arising from the listed trends are organized by categories, such as grid properties, network convergence, grid structure, generation, load, control, data and communications, and operations and markets. Although, the nation's electric power system is a highly complex system that continues to rapidly transform because of a combination of advancing technology, evolving regulatory structures, and changes in society, it is becoming even more complex with increasing dependencies and dynamics arising from renewable energy resources, electric vehicles, distributed generation technologies, and external stressors—both natural and man-made. With the emerging grid characteristics such as grid volatility, fast system dynamics, and increasing requirements of system resilience, cyber and physical security and decarbonization, on top of aging infrastructure and legacy structures, today's U.S. grid is facing unprecedented risks and challenges. New methods and tools are needed to help decision makers to manage complexity, identify hidden interactions and technical gaps, and make the correct decisions as changes are made to modernize the grid.

Acknowledgments

This material is based upon work supported by the US Department of Energy, Grid Modernization Laboratory Consortia (GMLC) 1.2.1 Grid Architecture Project, under contract number DE-AC05-00OR22725.

Contents

1.0 Introduction

Today's AC electric power systems are closely rooted in the design principles of the early-to-mid twentieth century when the electric power grid (the "grid" in this document) grew with the centralizing principle of economies of scale and was operated as unidirectional, especially in distribution grids. While emerging technologies have surged and our societal structures have changed dramatically, the power grid architecture has not changed fundamentally to accept these changes swiftly and seamlessly. Historically, the grid's relative inflexibility is a source of vital stability both for electric structure and management complexity reasons. However, this creates various difficulties when faced with new technology developments such as increasing renewable energy integration, ever-growing adoption of electric vehicles, distributed generation and energy storage, and new challenges such as cyber-attacks, and weather related threats.

Over the course of the last part of the 20th century and into the 21st century, there have been increasing market-driven and policy-driven shifts from vertically integrated to horizontally structured operations and from centralized to distributed electric power generation and delivery. Today's electric power grid operators and designers face the challenge of creating an architecture that accommodates a host of diverse requirements. The grid's modes of operation must accommodate concerns of reliability and stability, new deployments of variable renewable energy resources, threats from cyber-attacks and natural disasters, and increasingly distributed system operations. Grid modernization calls for a reliable, affordable, sustainable, agile, secure, and resilient grid. However, the modernization of the U.S. power grid is hampered by mounting complexity and diverging objectives from owners and operators and is consequently highly risky and fraught with design challenges. Flawed architecture, design, analysis, planning and operation will lead to potential stranded investments and lost opportunities for efficient resources and system use. A principled approach to minimize risk and develop a robust grid of the future is to begin with a sound architecture for the grid to inform the design process. Architecture development starts with the context of influencing factors that provide constraints as well as driving goals. This report provides the context of emerging trends and cross-cutting systemic issues in the U.S. electric power grid and serves as a vital input for grid architecture development.

Emerging trends are factors that are often exogenous to the grid today and influence its evolution. These could be technology, policy, or societally driven and cause the grid to evolve and adapt if and where necessary to the new trends. Systemic issues are structural and run-time conditions of grid operations that are extant in the grid and deserve to be addressed to support new requirements and objectives. New trends and systemic issues arise over time. Today, the U.S. electrical power grid is facing challenges of aging infrastructure, natural extreme events, and cyber-attacks [1,2], and demands modernization.

This document presents a listing of emerging trends and the cross-cutting systemic issues as source material for grid architecture development. These systemic issues and emerging trends are organized by vertical categories including generation, load, control, protection, sensing and measurement, data and communications, modeling and analysis, operation and planning, business and markets, as well as grid structures and properties.

2.0 Emerging Trends

2.1 New Grid Properties

2.1.1 Increasing focus on grid resilience

With wide-spread extreme natural disaster events in the last decade like hurricanes in the East and Southeast U.S. and wildfires in the west, grid modernization has emphasized operational and technological approaches to improve power grid resilience – a performance measure adding to the existing metrics such as reliability, stability, security, efficiency, and affordability. Various definitions of resilience exist. In 1973, Crawford S. Holling, a Canadian ecologist, defined resilience as a property of any ecological system which measures the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables [3]. Before this concept was introduced into power systems, the electricity sector adopted reliability predominantly as the risk management measures, which is defined by the North American Reliability Corporation (NERC) to be the abilities of adequacy and security [4]. In 2009, the National Infrastructure Advisory Council (NIAC) defined "infrastructure resilience" as the ability to reduce the magnitude and/or duration of disruptive events [5]. The effectiveness of a resilient infrastructure or enterprise depends upon its ability to anticipate, absorb, adapt to, and/or rapidly recover from a potentially disruptive event." In 2013, U.S. Presidential Policy Directive PPD-21 [6] uses the term "resilience" as the ability to prepare for and adapt to changing conditions and withstand and recover rapidly from disruptions such as deliberate attacks, accidents, or naturally occurring threats or incidents.

While the framework [7-9] of power system resilience and the quantitative metrics [10,11] to measure the resilience at both power transmission and distribution levels are still evolving, various grid hardening, and operational approaches have been adopted by utilities to enhance the resilience [12]. Generally, the grid resilience could be improved through two key abilities: the ability of the system to withstand all kinds of extreme events and the ability to restore the system back to normal conditions with fast and efficient restoration measures. Considering the low probability of extreme events, the latter ability is more practical.

With today's technology maturity and the availability of hardware infrastructure invested by the smart grid funds, power system operation can be optimized to further improve system resilience without breaking the regulatory and cost constraints. But a long-term resilience vision is to shape the future power grid structurally and intrinsically adaptable and elastic to continuously changing and dynamic conditions from either climate or cyber events. Fig. 1 illustrates different network architecture options [13], and from network perspective, a distributed architecture demonstrates more resilient salience. We can envision the future power grid will be moving towards distributed power systems with systems-in-system structure and a potentially flattened grid architecture.

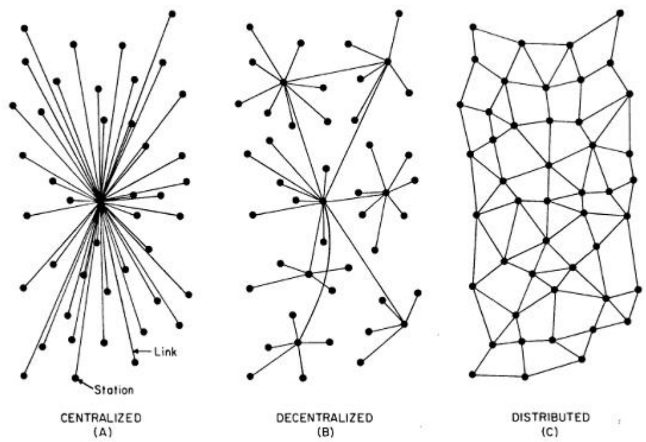

Fig. 1. Different network architecture [13].

2.1.2 Increasing focus on grid physical and cyber security

Cyber-physical security is another increasingly important modern grid property. In today's highly connected world, with an increasingly sophisticated cyber-threat, it is unrealistic to assume energy delivery systems are isolated or immune from compromise. With the 2015 power grid incident in Ukraine, attacks on power grids are no longer a theoretical concern [2]. Smart grid has applied communication and digitization technologies and poses vulnerability for an adversary to exploit under various circumstances. In October 2009, U.S. Department of Homeland Security (DHS) established the National Cybersecurity and Communications Integration Center, a 24-hour, DHS-led coordinated watch and warning center, to serve as the Nation's principal hub for organizing cyber response efforts and maintaining the national cyber and communications common operational picture. In 2011, U.S. Department of Energy (DOE), Office of Electricity Delivery and Energy Reliability, updated its roadmap to achieve energy delivery systems cybersecurity that envisions resilient energy delivery control systems designed, installed, operated, and maintained to survive a cyber incident while sustaining critical functions [14]. The energy sector is aware of this need—more than 80 stakeholders participated in the roadmap update. In 2018, a new dedicated Cybersecurity, Energy Security and Emergency Response (CESER) Office is established under DOE to support its expanded national security responsibility. DOE-CESER has invested more than $240 million in cybersecurity research, development and demonstration projects that are led by industry, universities, and National Labs [15].

The U.S. electric grid is vulnerable to cyberattacks that could result in catastrophic, widespread, lengthy blackouts and other loss of electrical services. In March 2021, A report by the US Government Accountability Office (GAO) review grid distribution systems' cybersecurity [16]. This report (1) describes the extent to which grid distribution systems are at risk from cyberattacks and the scale of potential impacts from such attacks, (2) describes selected state and industry actions to improve distribution systems' cybersecurity and federal efforts to support those actions, and (3) examines the extent to which DOE has addressed risks to distribution systems in its plans for implementing the national cybersecurity strategy.

2.1.3 Increasing focus on grid decarbonization

Countries and corporations around the globe are talking up their climate credentials, pledging to achieve “net-zero” carbon emissions or become “carbon neutral” in the next few decades. Among them, the U.S., UK, and EU all aim to move to “net-zero” carbon emissions no later than 2050. China and India aim for the same in 2060 and 2070, separately. One fifth of the world’s 2000 largest public firms have committed to net zero targets, according to a new report by the U.K non-profit Energy and Climate Intelligence Unit (ECIU) [17]. Qualcomm, AstraZeneca, and Alaska Airlines all plan to eliminate carbon emissions by at least 2040, while other corporations like Apple have committed to 100% carbon neutral supply chains and products by 2030.

Currently, nearly 40% of all carbon dioxide pollution comes from power plants burning fossil fuels to create the energy we use every day. Therefore, a key lever for achieving the decarbonization ambitions of the United States is to transition from burning fossil fuels for transportation and heating to using “clean” electricity generated by renewables. In April 2021, the United States set a target to create a carbon pollution-free power sector by 2035 as an important element in the country’s goal of achieving net-zero emissions by 2050 [18]. That means we need to revolutionize how we generate and use electricity, by making renewable energy sources like wind and solar more abundant, more affordable, and more accessible to everyone. For this reason, in March 2021, US DOE announced two bold goals: to deploy 30 gigawatts of offshore wind within the decade and cut the current cost of solar energy by 60% by 2030. These announcements are a big deal for combating the climate crisis, recovering from the economic slowdown caused by the pandemic, and addressing energy justice.

2.2 Network Convergence

2.2.1 Gas-electricity convergence and connections of midstream gas-fired generation

The operations of electricity and natural gas systems in the United States are increasingly interdependent, a result of a growing number of installations of gas-fired generators, the widespread availability of low-cost natural gas, and rising penetrations of variable renewable energy sources. In particular, small (less than 20 MW) gas-fired generators are increasingly connected to natural gas pipeline at midstream points, instead of at the typical downstream delivery points. This allows the generator operator to purchase gas more cheaply than from endpoint suppliers and allows "shallow” suppliers to have a path to market that was blocked due to gas transmission congestion.

This interdependency suggests the need for closer communication and coordination among gas and power system operators to improve the efficiency, reliability, and resilience of both energy systems. A recent report of National Renewable Energy

Laboratory (NREL) found that intraday coordination among gas and power system reduces total power system production costs and enhances natural gas deliverability, yielding cost and reliability benefits [19].

This also leads to the implications for coordinated planning of integrated electricity and gas infrastructures, which can decrease congestion in both electric transmission and gas transmission. Co-optimization of gas energy and electricity may also help improve energy efficiency and avoid peak demand in the wholesale market [20].

At distribution level, the coupling and interactions among various energy systems, such as power grids, natural gas networks, heating systems, etc., have been significantly strengthened. Around the interactions and interdependencies among the various energy systems in this transition, the concept of an integrated energy system (IES) has emerged [21]. IES is an innovative energy architecture that interconnects diverse energy systems via the coupling technologies, such as combined heat and power (CHP) units; power to gas units; heating, ventilating, and air conditioning (HVAC); heat pumps; and others and operates these coupled energy sections in a holistic framework. Through exploiting synergies and complementarities of the multiple energy systems to design and operate the energy infrastructures, the IES could potentially bring several benefits, e.g., improving system efficiency and flexibility, facilitating renewable energy integration, reducing carbon emission, and innovating new business models [22].

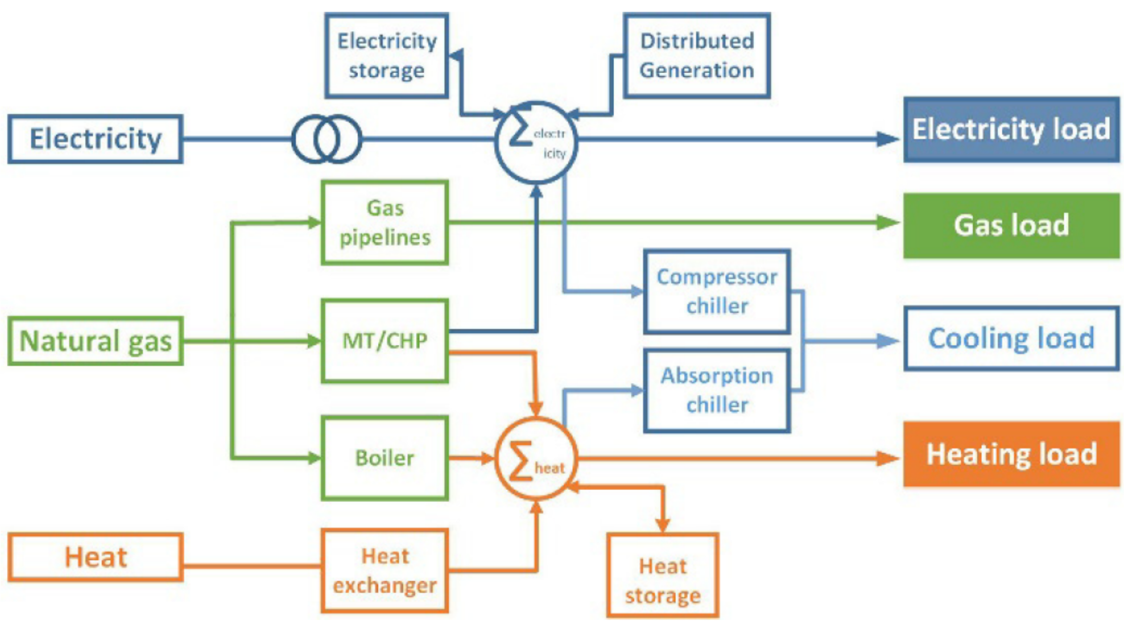

Fig. 2. Integrated Energy Systems [21].

2.2.2 Continuing convergence of information and communication technologies with power grid

The information and communication technologies (ICT) impact all levels of the grid, consumers, and utilities, thanks to the decreasing cost of both computing and networking, the synergy of combined computing and networking, and the prevalence of embedded computing in a wide variety of grid and edge devices, the need to provide increasing levels of wide-area situational awareness regarding grid conditions, and the promise of enhanced operational efficiencies [23].

Many utilities throughout the country have begun investing in the build-out of sensor systems and networks at the distribution level, particularly Advanced Metering Infrastructure (AMI), consisting of smart meters, communication networks and information management system. This ICT-power grid convergence implies common architecture for synergy, and development of new value streams, both of which are emerging in the utility world, e.g., the gradual move toward using communication and edge devices as application platforms.

2.2.3 Building to grid convergence

Commercial building owners and grid operators are recognizing the potential value of going beyond traditional demand response programs to allow for two-way exchange of energy services. This vision of a smart, two-way grid interacting with intelligent, responsive buildings can deliver new opportunities to save costs for building owners, operators, utilities, and operators. As responsive assets, buildings can ramp energy use up or down depending on the cost or carbon intensity of the utility generation source. This helps utilities ensure the balanced, flexible supply and demand of high levels of renewables and decarbonize the electricity system, resulting in resilient cities, communities, and regions.

Grid-interactive efficient buildings (GEBs) combine energy efficiency and demand flexibility with smart technologies and communications to inexpensively deliver greater affordability, comfort, productivity, renewables integration and high performance to America's homes and commercial buildings. Given the enormous untapped opportunity, the U.S. Department of Energy (DOE) is announcing a national goal for GEBs: To triple the energy efficiency and demand flexibility of the buildings sector by 2030 relative to 2020 levels. A national roadmap for GEBs has been developed by US DOE, Office of Energy Efficiency and Renewable Energy (EERE) in May 2021 [24].

The building to grid integration involve not only interface specifications but at a higher level, logical function specifications so that the control systems on both sides have something to say once they are able to talk to each other. There is a trend to develop a standard energy services interface (ESI) [25, 26], which is based on service-oriented architecture and provides a common interface for building responsive loads to offer energy services.

2.2.4 Transportation to grid convergence

With the growing concern for climate change and greenhouse gas (GHG) emissions, the electrification of the transport sector has attracted growing attention as a possible solution to reduce the GHG emissions and improve the air quality. The transition to electrical vehicles (EV) is well underway. According to the U.S. Department of Energy, there have been more than 1 million EVs on U.S. roads as of October 2018 [27]. A recent report released by Edison Electric Institute and the Institute for Electric Innovation projects that the overall number of EVs on U.S. roads is projected to reach more than 18 million in 2030 [28].

The massive increase in EVs will require large scale deployment of residential and public charging facilities, which presents a challenge for utilities. The significant increase in electricity needed to charge a growing number of EVs, particularly at peak times, requires utility companies to include EV load projections in their planning and develop charging programs that will best utilize EVs as a flexible resource, providing additional protection to the grid in case of emergencies, and helping support the increasing integration of renewable energy into the power system [29].

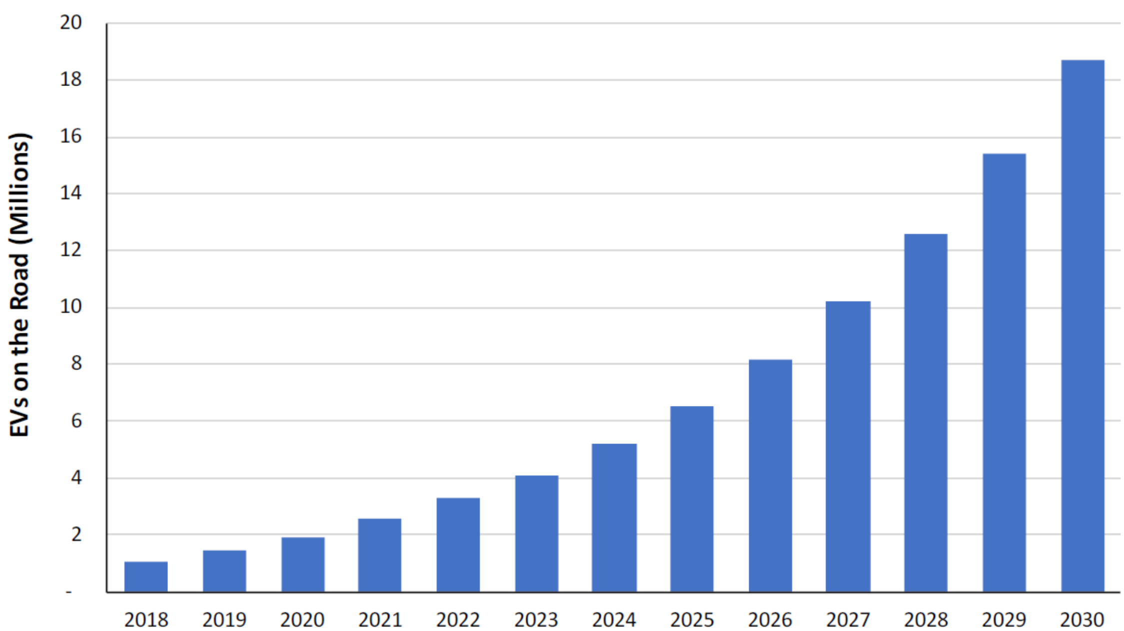

Fig. 3. EVs on the road of U.S. forecast [28].

2.3 Grid Structure

2.3.1 Microgrids as a Building Block for Future Grids

A microgrid is a low-voltage distribution system comprising various distributed energy resources and energy storage systems that are co-located with loads, and they have the ability to automatically transform from grid-connected mode into islanded mode. Microgrids can continue to serve its islanded portion without any interruption in case of utility grid failures. By virtue of their defining characteristic, microgrids introduce many unique opportunities, including enhancing grid resiliency, improving the reliability of power supply, integrating various renewable energy resources, reducing carbon emissions, improving energy efficiency, delaying investment in power system expansion, participating in voltage and frequency regulation, and encouraging customer interactions. Considering all these benefits, an increasing number of microgrids have been deployed by utilities, university and hospital campuses, military bases, and industrial parks in recent years.

According to a recent report published in early 2020, there are around 2,430 operational microgrid projects across the United States, developed by 187 developers [30]. Microgrids are evolving as the fundamental building block of this future grids, all over the world. The US DOE Microgrid R&D program envisioned microgrids to be essential building blocks of the future electricity delivery system to support resilience, decarbonization, and affordability, by 2035. Microgrids will be increasingly important for integration and aggregation of high penetration distributed energy resources. Microgrids will accelerate the transformation toward a more distributed and flexible architecture in a socially equitable and secure manner.

2.3.2 Modern grids evolving into ultra-large full-scale systems

The traditional vertical separation between transmission system and distribution system is becoming vague. Whole power delivery systems, taken from the interconnection level all the way past utility boundaries to connected distributed energy resources (DER) and demand response (DR), etc., have the properties of ultra-large-scale systems (ULS), meaning that the System of Systems (SoS) and similar paradigms are not sufficient to guide architecture and design for modern grids.

Power grids have System of Systems characteristics, but SoS alone does not provide sufficient insight for architectural improvement. ULS models treat systems as having (a) inherently conflicting diverse requirements; (b) decentralized data, development, and control; (c) continuous evolution and deployment; heterogeneous, inconsistent, and changing elements; and (d) normal failures. This is a much better view on power systems than SoS alone.

2.3.3 Grid structural scalability in both upward and downward directions

Grid architectural structures should be inherently scalable. There is a trend for grid to apply scalability in both upward and downward directions. The upward scalability is obvious, but it must be possible to scale downward to fit any particular utility or extended grid elements and subsystem, e.g., inside a grid-responsive building.

Scalability has three dimensions:

- scalable for the number of endpoints and edge-devices;
- scalable for geographic range and physical complexity, e.g., service area inter-penetration;

- scalable for functional and interaction complexity (often implies computation speed requirement).

2.4 Generation Diversification

2.4.1 RPS and other regulations pushing VER penetration

The trend of changing from traditional thermal generation to renewables such as solar and wind, also known as Variable Energy Resources (VER), is supported by public policy at the Federal government level and also at the state government level through Renewables Portfolio Standards (RPS). The Biden administration is aiming to set a national clean energy standard (CES) for the United States to obtain 80% of its power from clean, emissions-free sources by 2030. This 2030 aim will be a major step for the US towards reaching net-zero emissions by 2050.

Since wind and solar photovoltaics (PV) do not provide the rotational inertia of the traditional generation they displace, system inertia is gradually decreasing. In California, this will be accelerated by implementation of the once-through cooling regulation that will cause shutdown of coastal gas-fired plants between 2017 and 2022. Moreover, the VER is not dispatchable the way traditional generation is, and new control problems arise for a system originally designed around the concepts of power balance and load-following generation control [31]. Currently, the inertia reduction issue has not yet reached serious proportions in bulk power grids, but this problem is on the radar screens of several utilities such as Southern California Edison (SCE). Solutions to these problems may involve new types of grid components and controls, and re-purposing of older device types with new controls.

2.4.2 Changing fuel mix

U.S. utilities have made a significant move away from coal-fired power generation in the past decade, evidenced by a continuing stream of announced coal plant retirements. According to data from the U.S. Energy Information Administration (EIA), 121 U.S. coal-fired power plants were repurposed to burn other types of fuels between 2011 and 2019, 103 of which were converted to or replaced by natural gas-fired plants. At the end of 2010, 316.8 gigawatts (GW) of coal-fired capacity existed in the United States, but by the end of 2019, 49.2 GW of that amount was retired, 14.3 GW had the boiler converted to burn natural gas, and 15.3 GW was replaced with natural gas combined cycle [32]. The decision for plants to switch from coal to natural gas was driven by stricter emission standards, low natural gas prices, and more efficient new natural gas turbine technology. As the U.S. coal-fired electric generation fleet continues to manage challenges from emission standards and low prices for natural gas, EIA expects more of these conversions to take place in the future, particularly in the Midwest and Southeast.

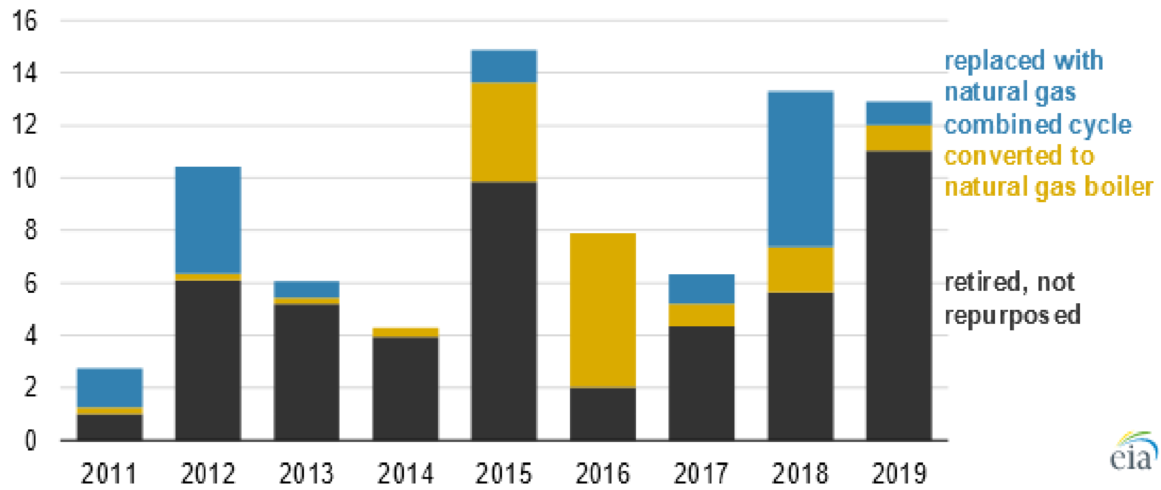

Fig. 4. U.S. coal-fired capacity retired or repurposed to natural gas by conversion type (2011-2019) [32].

Retirement of coal-fired power plants and their replacement by natural gas fired ones will lead to reduced diversity of generation fleet. This will eventually lead to increase in natural gas prices, as domestic and international demand increases. Reduced diversity in generation fleet will expose customers to increased energy price volatility due to weather related events, as experienced during the polar vortex in the northeast US in December 2013.

Since the markets for electricity and for natural gas have evolved separately, there is also the issue of "meshing friction" when both markets must be used to support generation, as happened in the winter of 2013-2014. Basically, these markets operate on differing time scales and rule sets, so that coordinating gas fuel and pipeline services for generation in unusual peaking conditions is complex.

2.4.3 Energy storage increase driven by policy and need

Electrical Energy Storage (EES) refers to the process of converting electrical energy into a stored form that can later be converted back into electrical energy when needed. Energy storage technologies include batteries, flywheels, compressed air, pumped storage, and thermal energy (such as molten salt and ice). Energy storage can interconnect at the transmission system, the distribution system, or behind the customer meter.

Energy storage is an important tool to help integrate increasing amounts of solar and wind electricity generation into the grid, reduce greenhouse gas emission, reduce demand for peak electricity generation, defer or substitute for an investment in generation, transmission, or distribution, improve the reliable and resilient operation of the electrical transmission and distribution grid. Addition of energy storage at various scales and attached at various points in the grid hierarchy can significantly change grid operations, economics, and control requirements. Meanwhile, energy storage costs are being driven down by technology advances and market forces. Due to these reasons, significant amount of energy storage has been deployed in the U.S. in recent years. In 2020, the U.S. had over 24 GW of energy storage capacity compared to 1,124 GW of total installed generation capacity [33]. Globally, installed energy storage capacity totaled 173.7 GW [34]. In 2021, 1,363 energy storage projects were operational globally with 11 projects under construction. 40% of operational projects are located in the U.S., despite COVID-19-related supply chain delays. California leads the U.S. in energy storage with 215 operational projects, followed by Hawaii, New York, and Texas [35].

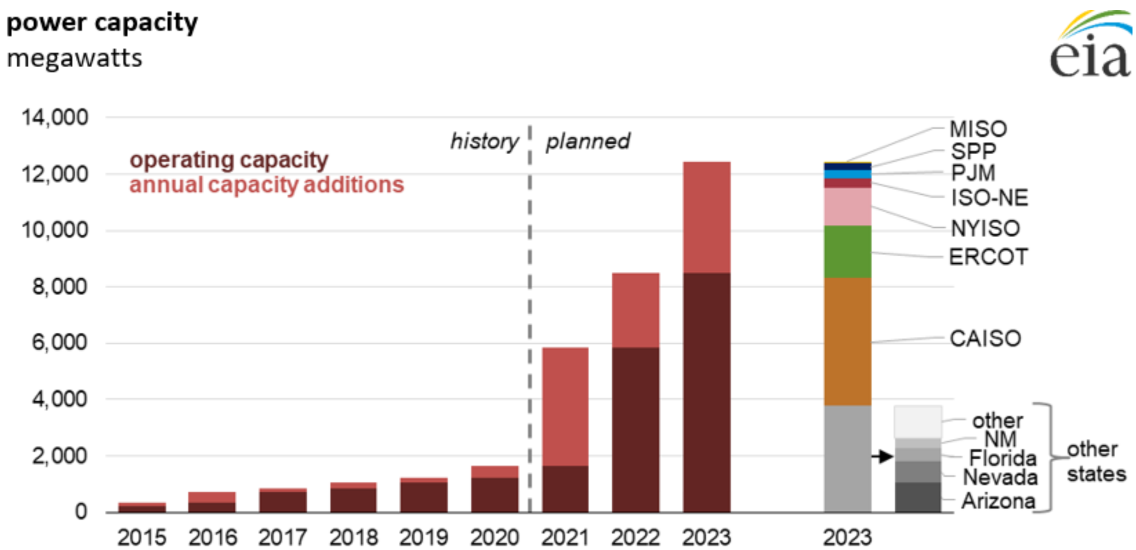

Fig. 5. Large-scale battery storage cumulative power capacity in U.S. (2015-2023) [33].

Multiple use cases for energy storage are identified. In addition to the obvious uses such as leveling out the variations of stochastic sources, storage can be used to supply certain ancillary services, e.g., up and down frequency regulation, and could be used for entirely new services such as virtual synchronous generation for replacement of lost rotational inertia.

Energy storage can be useful for augmenting system inertia via advanced control. Fast, bilateral storage combined with power electronics and advanced controls has the potential to become a standard grid element, as basic as a transformer or circuit breaker. This means it can become pervasive at all levels of the grid and can impact functionality (thereby creating new value streams) as well as reliability and resilience. At some levels, storage penetration is paced by the way in which grid services are structured into markets. New market "products" and changes in regulation will be needed.

2.4.4 Development and deployment of Inverter-Based Resources

As the generation portfolio changes, synchronous equipment that traditionally provide services necessary for stable grid operation is being replaced by inverter-based resources (IBRs), such as wind, solar photovoltaic, and battery storage. With the ever-growing dependence on IBRs, IBRs must become a primary support for stable grid operation.

Beside basic energy feeding and power conversion, IBRs have the potential to provide additional services, such as those delivered through synchronous inertia and synchronous torque functionalities, which are not inherent in IBRs. Nevertheless, these functionalities could be enabled in IBRs with additional costs, i.e., making inverters smart. The concept of smart inverters was originally proposed for solar PV inverters to provide ancillary services and grid support functions beyond basic energy feeding and power conversion [36]. Now, it has been extended to all types of IBRs, such as energy storage, etc., [37]. To enable a future grid with high IBRs penetration, the functionalities provided by smart inverters are essential [38].

Control of large numbers of independently owned IBRs (independent from the utility and possibly from each other) raises several control issues and opportunities that present distribution control structure does not support well. These include coordination, fairness of dispatch if a services model is used, and how to resolve load sharing in real time. More generally, power electronics offers new abilities for stabilization, enablement of storage value streams, and improved flow control, irrespective of inverter applications for DER/VER.

2.4.5 Penetration of both dispatchable and non-dispatchable generation in distribution systems leading to a partial inversion of the generation model

Generation has traditionally been centralized and connected at the transmission level. Increasingly, distributed generation is being connected at the distribution level. Sources may be traditional spinning generation, such as diesel, natural gas, propane, and biomass, or renewables, such as solar PV, and thus a mix of dispatchable and non-dispatchable forms are evolving on distribution grids. Most of these generations are not owned by electric utilities.

As part of the RPS and VER trend, the generation model for power grids has been shifting form centralized generation connected to Transmission to a mix of that and distributed generation connected to Distribution. This shift changes grid operations drastically, introducing multi-way real power flows and other effects not included in original grid design assumptions. In addition, distributed generation may be able to offer services back to the grid operator, such as reactive power regulation.

A recent report from Wood Mackenzie Power & Renewables forecasts that the combined capacity of distributed energy resources (DERs) will reach 387 gigawatts by 2025, driven by $110.3 billion in cumulative investment between 2020 and 2025 [39]. Due to public policies such as net metering, feed-in tariffs, etc., much of this generation can connect to the grid and impact grid operations. Even when not grid-connected, they can impact grid operations by shifting usage to non-utility sources, thus reducing the growth of demand seen by the utility, as well as demand peak size. Sudden changes in distributed generations or distributed energy resources can look to the grid control systems like step changes in load, especially when DG resides in microgrids that can island at will. While grid codes exist for electrical interconnection and protection for DG integration, such as, IEEE 1547 [40], control coordination is less well developed.

This also causes a split in regulatory jurisdictions as well. Is DG considered bulk generation and/or generation capacity and therefore FERC jurisdictional? How do State level and Federal regulations mesh for DG? If distribution level markets for DER are created, how do those and bulk system organized markets coordinate?

2.4.6 Bifurcation of generation into two classes: central and distributed

Partial inversion of the generation model has split regulatory oversight for generation due to recent FERC jurisdiction ruling; generation that exists at different tier levels causes tension in control regimes. The proliferation of distributed generation attached to the distribution grid has caused generation to change from purely a bulk power system issue (with FERC/NERC oversight) to that plus state Public Utilities Commission (PUC) level regulation for distribution level generation assets, even though the distributed generation assets may be dispatched for regional system balancing purposes. This issue also has market design and control system structural and algorithmic implications.

2.5 Load

2.5.1 Loads are becoming responsive

Loads have traditionally been passive in terms of grid control and generally forecastable in terms of demand aggregated to the feeder level and above. Increasingly, loads are becoming responsive, even transactive, with the penetration of various demand response programs. Demand response has been used by the utilities for decades, mostly in conjunction with commercial and industrial customers, and mostly in a non-automated fashion.

Nowadays, efforts have been made to develop to create automatically responsive loads at the commercial building level, at the residential level, and even at the individual appliance level [41]. Going forward, high speed dynamics are envisioned for local energy balance and new energy services, some offered by third-party Electric Services Operators (ESO) and potentially involving ancillary grid services. Consequently, grid and grid control as well as coordination must extend beyond the boundaries of the utility; control becomes more complex as dynamics of interactions matter at scale.

With the rise of advanced metering infrastructure, behind-the-meter storage, wide area communications, bulk power markets, and evolving approaches to “transactive” load coordination and control, the concept of building-to-grid is moving to a bidirectional multi-services model, which means it is possible that a grid-buildings convergence is forming. This will result in an emergent platform, which is a point of interdependence for buildings and grids at the control level and grid services levels, as opposed to just the electric service (to the building) level. Ultimately, this will result in the grid becoming an extended grid (involving assets not owned by the utilities) and the observability and controllability issues for grid will extend to include responsive loads.

2.5.2 Load composition is changing

Loads are changing from simple passive forms to more active forms dominated by nonlinear power supplies and by increasing embedded intelligence. According to a Smart Electric Power Alliance (SEPA) report released in October 2019, over 20 million EVs are expected on U.S. roads by 2030 [42]. This could change the utilities' load pattern significantly, such as shifting the utility's entire residential peak load to nighttime hours, etc. In some cases, loads are increasingly nearly self-sufficient, or can perform in a net-zero energy mode over some time period. This trend involves implications for controllability and responsiveness, as well as impacts on business models, and energy value streams.

2.5.3 DG/DER/DR are hiding real demand and introducing apparent load volatility

The deployment of both DG and DER is making the demand on the grid less, but when DG and DER are not firm, as it the case with much of it, then the grid operators must be prepared to support the full load, often on very short time scales. DR can also add to this issue if used in a non-coordinated manner.

These elements effectively introduce new apparent volatility in demand, which is problematic for balancing and distorts capacity market signals since they can make it appear that less traditional generation is needed than must be available to back up non-firm DG/DER.

Advanced control methods that combine bulk system and distribution issues and that simultaneously control power and energy states are needed. These must work in the context of new industry structures such as Distribution System Operators (DSO).

2.5.4 Diversity of load is expanding to diversity of generation

Traditional generation has been dispatchable (this includes fixed generation which is dispatchable by turning it on and off), while renewable sources such as wind, solar, and tidal are not dispatchable and behave in a random manner so are difficult to forecast. Traditional grid control assumes dispatchable generation and no storage. Thus, penetration of stochastic generation sources impacts grid control and economics.

The balancing problem is considerably aggravated by stochastic generation sources, as is the closely related system frequency regulation problem. Randomly variable generation is inconsistent with the load-following approach of standard balancing and automatic generation control (AGC), which is the basis for large-scale power grid control. Oversupply of power from wind or solar can cause not just balancing issues but voltage regulation problems, congestion issues on transmission, market issues (negative marginal prices for wind energy) and investment issues (large wind curtailment due to transmission capacity, balancing capacity and ramping issues with combined cycle gas that can be turned down to 40% as opposed to coal at 20% - this impacts Debt Service Coverage Ratio (DSCR) and causes additional equity payments from investors).

2.6 Control

2.6.1 Faster system dynamics

Power system dynamics are increasing in speed and decreasing in latency requirements by orders of magnitude. The implementation of new grid capabilities has brought with great increases in the speed with which grid events occur. This is especially true on the distribution grids, although the trend exists for transmission as well. In the last century, aside from protection, distribution grid control processes operated on time scale stretching from about five minutes to much longer and human-in-the-loop was (and still is) common. With the increasing presence of technologies such as solar PV and power electronics for inverters and power flow controllers, active time scales are moving down to sub-seconds and even to milliseconds. Consequently, automatic control is necessary, and this brings with it the need to obtain data on the same times scales as the control must operate. Consequently, there is a sort of double hit: many more new devices to control, and much faster dynamics for each device, leading to vast new data streams and increasing dependence on ICT for data acquisition and transport, analysis, and automated decision and control.

At the bulk power level, the 2003 cascading blackout showed that events could happen at speeds far too fast for human operators to manage and Phase Measurement Unit (PMU) data rates are now typically 30 to 60 readings per second, which is already too much for human operators to comprehend at the raw data level. Existing person-in-the-loop control is becoming unsustainable; existing control systems and related applications are becoming unable to keep up with real grid behavior. Additionally, data acquisition is impacted since latency and latency skew become much more significant as control time cycles decrease. The need to synchronize sampling is not just about being able to compare phase, it is also about being able to assemble a state snapshot that does not have significant errors due to sample time skew.

2.6.2 Hidden feedbacks and cross-coupling

As more advanced grid applications and systems are developed and deployed, there are increasing opportunities for system interactions. These interactions are inevitable, contrary to the apparent viewpoints of some application developers. These interactions occur and will continue to occur because the grid itself constitutes a hidden coupling layer for all grid systems and subsystems.

The coupling occurs due to the electrical physics of the grid and this coupling propagates at nearly the speed of light in most cases. Such coupling can cause effects ranging from reduced effectiveness of a smart grid function, up to and including wide area blackout. Generally, effects of such interactions will not be important at the scale of pilot projects and demonstrations but will become significant as penetrations pass tipping points.

2.6.3 Evolving control system structure

Utility control systems have traditionally been centralized, with hub and spoke communication to remote subsystems and equipment as needed. As the various trends cited here have emerged, the need for changes in control system structure has become apparent. Specifically, control systems must change from being centralized to a hybrid of central and distributed control.

While the industry generally recognizes the need for a transition to more distributed forms of control, this cannot happen without vendor-developed products. The vendors see thin markets and are unwilling to commit to new product development investment until they are reasonably assured of a market; the utilities are unwilling to commit to buying until they can see how new controls would work for them and what support they would see at regulators for new expenditures on controls and communications.

2.6.4 Increasing complexity of grid control problems and application of optimization methods to solve them

Large scale grid control problems are becoming increasingly complex as we add new functions and requirements. In many cases, we wish to do optimization as a matter of the goals we seek to optimize load profiles, or minimize carbon emissions, for example. In other cases, we need to use optimization just to be able to solve the control problems at all. Present grid control systems are not structured for large scale optimization. The cross-tier modes are increasingly important: DER/DG should be dispatched from Balancing Authorities (VPP models). End users want to perform "selfish" control that conflicts with optimal system control but must consider impact on distribution operations to maintain grid stability and ensure efficacy of DER, for example.

Integrated Volt/VAR control is already formulated as an optimization problem with minimization of distribution substation transformer's load tap changer (LTC) operations as the cost function, constrained by keeping voltage in bounds [43]. Demand response problems are increasingly being formulated as optimization problems [44]. Electric vehicle charging control is now being formulated as an optimization problem to consider multiple constraints [45]. Optimization is not yet being widely applied at larger scale and across multiple utility/grid tiers but should be. It is needed to coordinate multiple controls and objectives, to take complex constraints into account, and to solve distributed control problems [46]. Optimality is not so much the issue as is the need for tools that can accommodate huge numbers of constraints and conflicting objectives. The presence of large amounts of mixed DER constitutes a new kind of control problem for the grid. These DER overlap somewhat in capability but also have differences in capability, behavior, and economics that should be considered operationally. Also, DER assets have different values at the bulk system level than they do for distribution but may be used by both.

2.6.5 Loss of system rotational inertia due to replacement of traditional generation with wind and solar PV

In bulk power systems with synchronous generators, the inertia response determines the initial rate of change of frequency (RoCoF) after a contingency. The generator governor response assists in arresting the system frequency before the protective schemes, such as underfrequency load shedding and overgeneration reduction, take effect. Then, the frequency is stabilized and restored to nominal by reserves.

While system inertia has a significant effect on the bulk power system frequency stability, wind turbines have low inertia, which is not always available, and solar PV has no inertia. Replacement of heavy rotating machines with high rotational inertia with wind and solar PV sources causes an overall system level decrease in inertia, resulting in a much higher RoCoF after a contingency, leading to exceedance of frequency limits before any countermeasures have time to respond and tripping of generation or load. Furthermore, protective devices triggered by a high RoCoF may aggravate these effects and cause system collapse.

2.6.6 Increasing number and penetration of new functions especially at distribution level

Functions are connected through the grid and may interact due to hidden coupling through grid electrical physics; coupling may not be recognized until a penetration tipping point has been passed (i.e., may not show in demonstration and pilot projects)

This leads to a multiple controller, multiple objective situations where applications want to make use of the same control element or infrastructure element for differing purposes [47] and has led to situations like over-writing of prices to devices, improper control operation, and reduced power quality as well as reliability.

2.6.7 Vastly increasing number of endpoints attached to the grid that must be managed, sensed, and/or controlled

Increasing sophistication and addition of new functions to the grid results in increasing numbers of devices with embedded processing and communication capabilities. These devices must be managed in the FCAPS sense. FCAPS is a terminology borrowed from the networking domain, meaning Fault (management), Configuration, Administration, Performance (monitoring), and Security. Those that have sensing, and measurement capabilities must be read; those that have control capabilities must be commanded or otherwise directed to action.

Control systems now handle sensing and control endpoints numbered in the thousands and network management systems now handle up to about 5 million devices. Widespread DER/DR penetration implies that a grid control system may have to handle 30 million to 100 million endpoints (aligned with a popular term in the first two decades of the twenty first century: internet-of-things or IOT), which existing grid control currently cannot accommodate [48].

2.7 Data and Communications

2.7.1 Increasing data volumes from the grid, increasing variety of data due to diversity of device types, and increasing observability

While much of the discussion around increasing volumes of data from the grid focused on meter data, in fact particularly large volumes are coming from and will continue to grow from newer instrumentation on both transmission and distribution grids. Eventually the more than 5,000 PMUs that will be installed on the US transmission grid will produce vast volumes of data at about 1.5 Petabyte per year. The vast amounts of data from PMUs are because these are streaming devices, much like video in that they produce streams of data (as often as 60 values per second) that are used at multiple destinations. Similar technology is about to start penetrating the distribution grids, which will have orders of magnitude more streaming sensing devices than will be found on the transmission.

In addition, as interest in asset monitoring continues to increase, vast new volumes of asset health and operational data will be generated, with some to be used in real time and some to be stored and analyzed later. Finally, newer protection and control systems needed for advanced grid functionality will generate enormous volumes of sensor data that must be transported, processed, and consumed in real time and be stored for offline analysis. All told, the utility industry will experience an expansion of data collection, transport, storage, and analysis needs of several orders of magnitude by 2030.

2.7.2 New desired capabilities raise new attentions for data privacy and confidentiality

Some approaches for transactive and other large-scale coordination methods require some information from prosumers to flow in the control systems. Certain data may want to be shared to facilitate transactions, but general security concerns still apply. Most schemes for secondary control of large numbers of endpoints assume sharing of some kinds of data that are not shared today.

2.7.3 Meta-data management

Much advanced grid capability, especially at the distribution level requires the management of large amounts of time-varying meta-data. Most grid ICT and control systems do not handle meta-data well, but more importantly, the meta-data is often inaccurate or not available. This is a special issue for distribution connectivity because it is often poorly known (connectivity models only 50% to 80% accurate) and is the context for all distribution grid data, events, and control.

2.7.4 Latency hierarchy

Grid data is consumed by a variety of applications and these applications define latency requirements that collectively form a hierarchy. This hierarchy has significant impact on architecture of the data management, analytics, and control systems.

Some data has multiple uses and so has multiple latency requirements. Some latency requirements are so short that the data must be processed close to the source and use points. This in itself implies a distributed (or at least decentralized) architecture for grid information processing and control.

2.7.5 Timing distribution for power system control and protection is shifting from GPS to PTP-based synchronization

Many grid operations require synchronization of applications that reside in geographically dispersed locations. Such applications include acquisition and processing of PMU data and grid protection control. For PMU's it is common to have local GPS timing data, but it would be more cost effective and flexible to use precise timing distributed over wide areas via Precision Time Protocol (PTP) and the communications network.

Such timing distributed is possible via the IEEE 1588/C37.238 standard [49]. The problem is that while very precise timing can be sent through the network, the means to get the timing into applications (NTP) without loss of precision or accuracy is lacking. Some work is being done at NIST on this issue and should be moved forward expeditiously so that product vendors and application designers can make use of it. This will allow reduced dependence on GPS and more flexibility is choosing clock sources.

2.7.6 Large-Scale Data Collection Driving Machine Learning (and Artificial Intelligence (AI)) and Automation

The growth of data analysis methods such as deep learning has led to a tremendous increase and interest in automation. Using larger amounts of data acquired from the grid and learning from patterns has created the possibility of new model-free and topology-agnostic control algorithms, rapid automatic control without a human-in-the-loop step, and significantly faster grid response to known states in the grid [50].

Although there is significant work remaining in creating fully automated operations in certain areas of the grid, new grid designs are being developed with the full awareness that the available computational power presents great potential to optimize and provide robustness to the grid.

2.8 Operation and Planning

2.8.1 Increasing need for advanced planning and operation- data, methods, and tools

As the grid ever-growing relies on VRE, like wind and solar, the attentional to reliability and weather conditions are increasingly important. Traditionally, resource adequacy analysis is used to determine if there are enough available capacity to meet the load, accounting for the uncertainty in generation availability, transmission, and load. By applying stochastic tools to evaluate these uncertainties, grid planners can calculate the risk of shortfalls and determine the how much investment the grids require, and how much new generation should be built [51].

Grid planning tools used today didn't consider the chronological grid operations and instead only evaluate the single peak load periods, assuming highest risk period occurs only during peak load periods. In addition, they often assume static load requirements and don't consider the energy limitations of most resources. These assumptions can no longer hold due to the integration of large amount of VRE, deployment of energy-limited resources, such as energy storage, etc., and increased load-side flexibility. To modernize the old framework of grid planning, new data, methods, and metrics to better characterize the evolving risks, weather fundamentals and climate changes are needed [52].

2.8.2 Coordination between balancing authorities

Many balancing authorities (BAs) have participated in reserve sharing groups to benefit from increased diversity of a bigger system and thus proportionately reduced the amount of operating reserve. The benefit becomes more significant as the penetration of variable generation (VG) goes up. Another form of coordination between BAs is energy imbalance market (EIM), which allows the transactions between BAs to happen at 5 to 15 minutes intervals on top of hourly schedules. EIM will help BAs to deal with the intra-hour variability brought by VG more effectively with a larger pool of resources.

The California Independent System Operator (CAISO) began financially binding operation of the western Energy Imbalance Market (EIM) on November 1, 2014 [53]. In the beginning, resources were only being optimized across the CAISO and PacifiCorp balancing authority areas. But since that time, NV Energy, Arizona Public Service, Puget Sound Energy, Portland General Electric, Idaho Power, and Powerex have become participants in the EIM. The footprint now includes portions of Arizona, California, Idaho, Nevada, Oregon, Utah, Washington, and Wyoming, even extending to the Canadian border. The EIM has enhanced grid reliability and generated cost savings for its participants. Besides its economic advantages, the EIM improves the integration of renewable energy, which leads to a cleaner, greener grid.

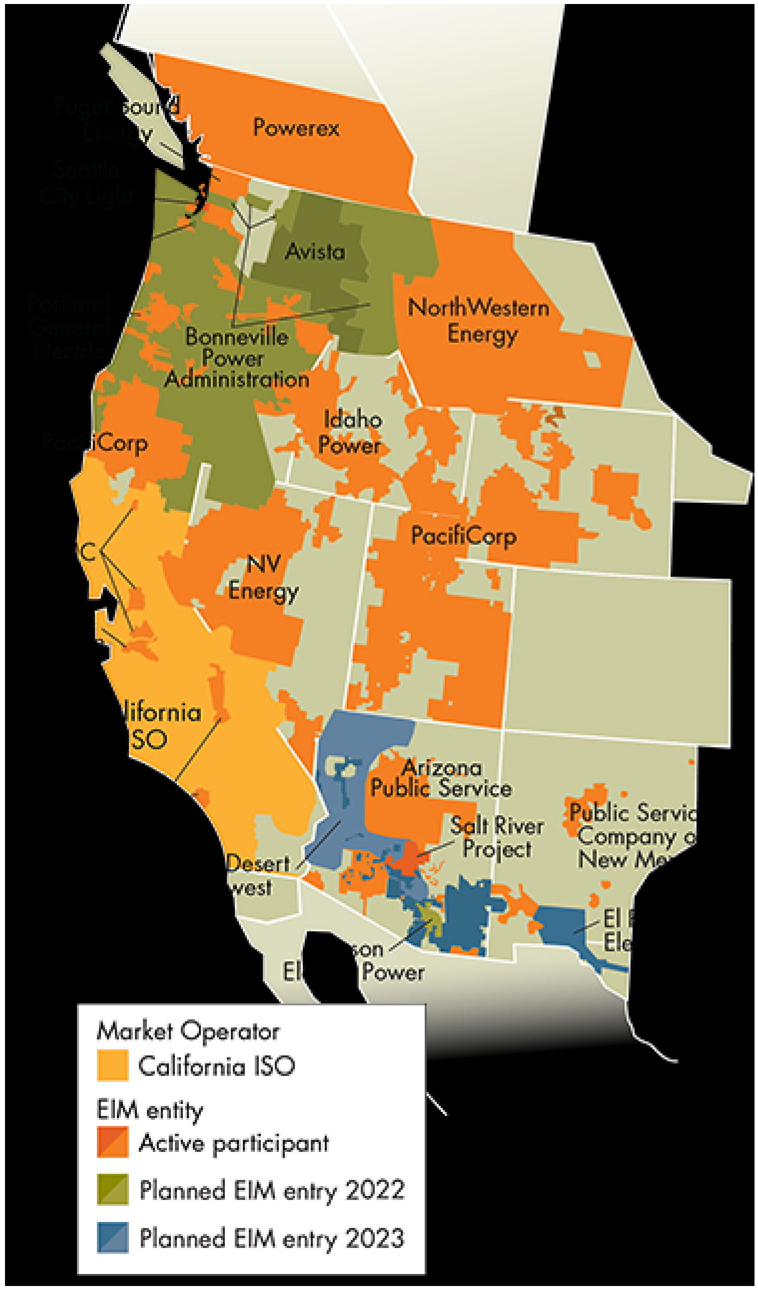

Fig. 6. Active and pending participants of western EIM [53].

2.8.3 T&D planning, operations, and regulation in an integrated manner as opposed to the fragmented way it is done now

Bulk systems and distribution systems are increasingly interactive, due to DER penetration and active load participation in grid operations. Joint T&D planning is needed, as well as integrated resource planning, not as in the past where the distribution was treated as a load floating on the transmission. New tools must support not only tradition planning criteria, but also include support for new market products and control/coordination approaches, as these will all be interconnected in the future grid.

2.8.4 Distribution operators changing to DSO models with significant structural implications

Evolving trends in the US utility industry are causing structural changes that are resulting in a growing mismatch between traditional roles and new requirements at both distribution and bulk system levels.

Models for distribution operators are changing to DSO models with significant structural implications. The partial inversion of generation model being caused by DG penetration, coupled with the growth of functions of microgrids and DR that mask load, and the implications of storage as a grid element mean that it is not possible to continue viewing distribution as a simple aggregated passive load "floating" on transmission. Changes in roles and responsibilities are being examined in the industry now and those potential changes have implications for grid control architecture.

2.9 Business and Market

2.9.1 Evolving change of business models and structure in distribution systems

It has become obvious that the penetration of new functions at the distribution level, along with responsive loads and distributed generations, is causing the original model of distribution operations to become inadequate. Proceedings in Hawaii, New York, and California are all aimed at reconsidering the roles and responsibilities of distribution grid operators as is much thought leadership in the industry at large.

The Distribution System Operator model for distribution operations is apparently taking hold in various locations, driven by the expansion of grid functions and inversion of the generation model being experienced in those locations. In some models, distribution level markets are intended to foster new penetration of DER and help manage DER-rich grids. No such markets exist and the ways in which such markets should be designed, integrated with grid controls, and regulated are as yet unresolved. The question of distribution providers as DSOs vs. independent DSOs is also unresolved.

2.9.2 Load aggregation and DG aggregation companies as power market participants

The proliferation of distributed energy resources (DERs) at the edge of the grid, such as residential solar photovoltaics and batteries, has created the opportunity for aggregators to manage multiple customers and their DERs to participate in energy and ancillary service markets and provide various local and system-level grid services. Demand response resources can also participate in the markets, after large numbers of such devices are lumped together by aggregation companies. This will increase the elasticity of demand in the energy market and help fully and more efficiently utilize available generation resources [54].

Existing utility companies can perform these two roles as well as new load and DG aggregators; however, DG aggregators such as solar leasing companies often target jurisdictions and geographies where existing utility rate structure gives them a competitive economic advantage.

2.9.3 Missing money and resource adequacy particularly in regions with restructured power markets

Increasing penetration of renewable energy sources, such as, wind and solar with low or zero marginal production costs, causes energy prices to drop. Hence, conventional resources, which are needed to maintain reliability in power supply, are increasingly facing issues of reduced revenues from the provision of energy and ancillary services. The missing money problem impacts resource adequacy, as being witnessed in ERCOT and other regional markets [55].

While regulated utilities owning both generation and transmission systems continue to meet resource adequacy requirements under the supervision of state regulators, restructured markets are trying to assure resource adequacy through market incentives assuming the power market model works well toward this direction. The reality is that the planning reserve margin, which is an indicator of resource adequacy, has become lower in restructured power markets over years and when compared to regions with regulated markets.

The resource (in)adequacy problem is especially problematic in the context of increasing sources of energy that are inherently intermittent. The issue of missing money also arises due to increasing retail choice and distributed generation, which collectively reduce a utility's customer base, and hence, the revenues. The issue has been tackled differently by various ISO's by either instituting long-term capacity markets (ISO-NE, NYISO, PJM) or by raising scarcity prices (ERCOT). However, most of these are stop-gap measures at best and will require a serious rethinking in the design of electricity markets. Some of the proposed solutions include letting market participants cover more than just the marginal production costs in order to recover capital and other operating costs, while allowing the markets to ensure adequate competition to mitigate market power, as well as provide appropriate market signals for future capacity building.

Resource adequacy issue gets more complicated with increased penetration of variable generation and distributed resources, even for regulated market regions. Distributed resources pose many unknowns to the planning process of regulated utilities, as well as restructured power markets, such as peak capacity, energy, availability, etc., making it more difficult to evaluate system resource adequacy and reserve margins. For restructured markets, these resources make the evaluation of profitability of new generation resources more uncertain and difficult, which could hinder investments on new generation resources. Low energy prices caused by significant amount of variable generation threats the viability of conventional generation and discourage new developments, while the amount of dispatchable resources could be in shortage to compensate for the variability of wind and solar resources.

2.9.4 Traditional value-of-service business models evolving to adapt to new grid requirements

Some grid investment decisions, especially those related to "grid hardening" and grid resilience are based on models of the value of electric service dating to the 1980's. Investment in measures that would improve grid resilience are hampered by undervalued grid service. By updating and regionalizing these models, it would be possible to provide regulators and investors with better understanding of the public good to be achieved by making grid resilience improvements.

New models for value flow and valuation of grid services to be produced by DER and other technologies will be increasingly important to grid modernization, but the tolls and methods to perform the analyses are lacking and not standardized. An example is the approach of “value stacking” to bundle grid applications to create multiple value streams [56]. These bundled applications increase the return on investment in the period of the investment, but potentially complicate operations with the mingling of retail and wholesale services.

2.9.5 Varieties of Consumer Choice

A variety of new choices is becoming available: smart vs. dumb appliances, kind of power generation desired, engaged or disengaged, power quality level vs. cost. In addition, markets or programs for residential DR are spreading. Consumers are increasingly looking to have more local control over energy choices though private DG, and through organization via microgrids, local energy networks, and via formation of Consumer Choice Aggregators (CCAs) [57]. The CCA’s are adopted into law in MA, NY, OH, CA, NJ, RI, and IL and can act as utilities in terms of both purchasing and generating power.

Value propositions are key to which choices will become more than theoretical. The movement toward localized generation leads to utility concerns of “grid defection” and a resultant “utility death spiral.” As more people pull off the grid, the cost of supporting it would fall onto those who are not able to leave. Some distribution utilities see a need to transform themselves from power delivery channels to open access energy networks. This raises technical issues (note: grids are not structured for this), as well as regulatory and public policy issues. Social network interactions also play a role as groups of end users, consumers and prosumers self-organize. (Even the terms prosumers are beginning to be used less and being replaced by separate references to consumers and DER owners.)

3.0 Systemic Issues

3.1 Grid Properties Desired: Leading to Deployment and Operational Complexity

A broad systemic issue revealed by the emerging trends in the Grid Property area (see Section 2.1) is the necessity to link multiple domains of interest and address the associated complexity. With the trend of focusing on grid resilience, physical and cyber security, and at the same time decarbonization with new technologies, the key issue facing grid designers is managing the complex structural and control needs of a complex grid. A similar theme emerges from the other trends listed in Section 2, but the underlying interest in improved grid properties as a trend drives complexity that is difficult to address in a straightforward manner.

The resilience requirements of power grids are major concerns at the national level after a series of widespread and large-scale extreme events like Hurricane Katrina (2005), Irene (2011), and Sandy (2012) resulted in disruptive damages to grid infrastructures and led to significant power outages. In recent years, the frequency and intensity of such weather-related incidents and natural disasters have been increasing [58]. Extreme weather is the leading cause of electric power outages in the United States, accounting for 80% of all outages between 2003 and 2012. Extreme weather-related outages cost the United States $20–55 billion annually, according to recent estimates [59].

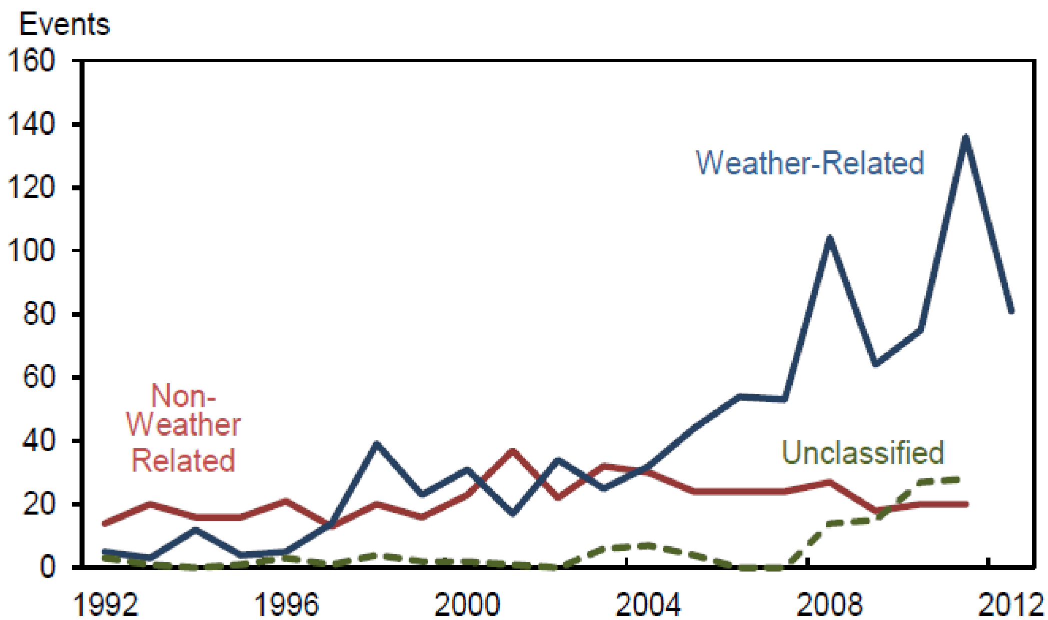

Fig. 7 Observed outages to the bulk electric systems in U.S., 1992-2012 [58]

Increasing attention is being paid to cyber-physical resilience and recovery from critical equipment failures, e.g., from transformer outages. The functions of other critical infrastructures, such as water, health care, and emergency response, rely heavily on electricity supply from utilities. Consequently, the power grid is asked to be even more resilient at withstanding event effects without dropping services, provide better ride-through for critical loads, and greatly reducing recovery and restoration times. Determining how to effectively enhance the resilience of the electric power system has become an urgent need and attracted worldwide intention from academia and industry. While various approaches to "hardening the grid" are known, the deployment of these measures depends on the ability to properly plan at both transmission and distribution (T&D) levels, as well as the ability to highlight the value of new services in justifying the needed investments. Establishing the value of these vital investments in a complex investment landscape is a systemic challenge.

Adding to grid deployment complexity is the diversifying generation mix. Wind and solar photovoltaics are the most fast-growing generation resources in the U.S., with approximately 200 GW of wind and solar now installed as the grid pushes towards the trend of decarbonization. Considering that the nation has approximately 1,200 GW of generation capacity and a relatively low capacity factor of wind and solar generation, to realize the target of creating a carbon pollution-free power sector by 2035, significant wind and solar photovoltaics must be deployed at a faster pace. (According to ZeroByFifty, 1 TW of new PVs and 1TW of new wind generation will be needed to meet 100% clean energy by 2050 [60]. To deliver these resources to loads, significant transmission will be needed. A recent study by MIT finds that the current high-voltage transmission will have to be doubled (in megawatt-miles) to reach 100% clean electricity [61].) The scale of wind and solar photovoltaics will be even larger if significant electrification, such as, building and transportation, occurs. This leads to systemic complexities that are hard to predict and contain.

3.2 Network Convergence: Gas-Electric, Building-to-Grid, and Transportation-to-Grid Leading to Unpredictable Interface Points

Collaborative efforts of multiple energy sectors are needed to achieve affordable and clean energy. Driven by the clean energy target, energy systems (e.g., electricity, natural gas, hydrogen, district heating, district cooling, electrified transportation) are undergoing a fast transition. This transition is reshaping and integrating multiple energy sectors involving various energy processes, from energy supply, energy conversion, energy transmission and distribution to energy utilizations. The couplings and interactions among the energy systems are significantly enhanced at various scales from national, region, urban, rural, community to buildings. These are leading to the systemic issue of multiple connection points that are growing unpredictably in the grid. In addition, the lines of responsibility are blurred across the converging domains.

The energy system integration requires new technologies such as energy storage and flexible energy demand management as well as new energy policies, business models and market mechanisms to enable synergetic interactions among the energy systems to improve the overall energy efficiency and reduce carbon emissions. The systemic issue of concern here is that the decentralized growth and convergence is likely to lead to a “spaghetti” grid.

3.3 Grid Structures: Proliferating Options and Deployment Inconsistency

As grids decentralize and distribution utilities, municipal systems, cooperative farms choose their own mechanisms for delivery, aggregation, and control the choices available to set up a grid structure proliferate. These lead to inconsistencies in strategies to store data, locate control, and to organize recovery in case of failures. This proliferation leads to a systemic issue of lack of consistency, uncertainty in best-practice adoption, and a variety of implementations. A diversity of implementations may lead to inconsistent and uneven grid modernization leading to an "impedance mismatch" of service availability and agility in delivery.

For example, affordability is a vital driving factor in how communities may choose their deployments and implementations, over concerns of future resiliency. In addition, there are several other technical, policy, and business barriers, such as interoperability and controllability of legacy electrical devices, protection coordination of the utility grid, neighboring microgrids and internal distributed energy resources, legal and regulatory issues, and supply chain challenges for key components. For example, different microgrid installations likely will use different technologies and vendors, and interoperability among the microgrids is a challenge that will need to be addressed.

3.4 Generation Choices: Decision and Control Complexity Increases

The supply and demand of the power systems must be kept in balance all the time. Initially, the reserve is introduced for balancing purposes under the scenario of load changes and generation outages. Taking into consideration the increasing penetration levels of power generation from variable and hardly predictable sources such as wind and solar energy, the flexibility of power systems, especially balancing and reserve requirements, need to be redefined. From an operational perspective, different types of flexibility are required, depending on timescale, such as, increased frequency response and reserves for seconds to minutes, increased ramp capability for minutes to hours, and scheduling flexibility for hours to a day. Cutting edge technologies including different control strategies, stochastic and robust optimization techniques, and energy storage devices will be employed to handle those issues.

FERC Order No.2222 opens the door to DERs in wholesale markets, allowing DERs/DER aggregators larger than 100 kW to participate and compete in all ISO/RTO markets. Incorporating and modeling a large number of small-scale DERs at the wholesale market level will become a significant challenge, but necessary to the operation of the ISOs/RTOs. The challenges faced by ISOs/RTOs are twofold: a) modeling a large number of DERs significantly increases the size and complexity of the unit commitment (UC) and economic dispatch (ED) problem, leading to much longer execution time; b) the capacity of DERs is too small compared to the magnitude of the mixed-integer programming (MIP) gap of the UC solver, leading to random schedules and payoffs for the small-size DERs, causing fairness/equity issues for DER owners as market participants.

Although high-level IBRs penetration reduces carbon emissions compared to conventional fossil fuel-based energy generation, control issues become more complex as the system inertia is significantly decreased due to the absence of conventional synchronous generators. Novel and existing stability phenomena are manifesting themselves during high-IBRs conditions. Challenges related to frequency, voltage, and phasor stability as well control stability arise due to high IBRs penetration.

As IBRs penetration grows, so does the complexity and hierarchy of control layers. These controls manage the state of the active and reactive current and power, voltage, phase angle, mechanical torque and speed, etc., in various locations and time frames. The coordination and interoperability of these control layers to maintain stability are becoming increasingly difficult, particularly in low-system-strength conditions.

3.5 Load Responsiveness and Variability: Dispatching Strategies are Unclear

Increasingly, loads are becoming responsive, even transactive. Traditionally, loads have been passive in terms of grid control and fairly forecastable in terms of demand aggregated to the feeder level and above. While Demand Response (DR) has been around at the commercial and industrial level for decades, more recently it has been applied at the residential and small business level with low-speed dynamics. Going forward, high speed dynamics are envisioned for local energy balance and new energy services, some offered by the third-party Energy Services Operator and potentially involving ancillary grid services. Consequently, grid and grid control/coordination must extend beyond the boundaries of the utility; control becomes more complex as dynamics of interactions matter at scale.

The distributed nature of generation will hide real demand and introduce apparent load volatility. In addition, stochasticity of generation increases the modeling complexity, making dispatching a new complex domain of grid engineering in which the engineering R&D needs to catch up with the speed of deployment. The determining trends of the changing load landscape may be summarized as:

Much grid control is still done in open-loop fashion, which is problematic in itself. Most closed-loop grid controls are simple PI controls which are siloed and are known to be weak in the face of high-order system dynamics. Regulation and stabilization of voltage, reactive power, and frequency are being impacted by emerging trends that make existing tools increasingly inadequate.

Traditional simple closed-loop and single-input single-output frequency domain control design methods are not able to handle multi-variable, multi-objective, multi-controller problems that are arising in grid control. Optimization methods have the ability to support complex performance goals and system constraints in a multi-variable environment. Note that the issue is not strict optimization (which is brittle) but the ability to get solutions to complex control problems. This approach allows relaxation of the optimization process to benefit fast solutions and provide a degree of robustness.

The tools need more powerful methods and must be much faster to accommodate new grid functions and complexity and the need to get ahead of faster grid dynamics and be integrated into closed loop control. Contingency analysis needs to be augmented with stochastic methods in addition to N-k methods; state determination must handle T&D jointly in unbalanced mode much faster than present transmission level tools. Tools must integrate communication networks and show effects of industry structure and regulatory and financial impacts.

3.6 Secondary Control Mechanisms: Exposing Poor Protection and Increased Vulnerabilities

The combination of social media and potential ubiquitous networking of ordinary objects ("Internet of Things") opens new possibilities for grid interactions that entirely bypass the grid control, communications, and security systems (and thereby all NERC CIP measures).

More than one person has pointed out the possibilities of extending the flash mob concept or simple hacker-based extortion to the control of home energy-using devices, so that significant amounts of demand could be manipulated on short time cycles to disrupt grid operations. If the IoT model of Internet-connected home devices becomes pervasive, this would potentially be a load control channel that entirely bypasses the utility, except for the electrical coupling through power circuits. The same is true for DR aggregators, but in that case, there is an organization involved (the ESO or aggregator) that could be held to some level of security responsibility. In the social media case, there is no centralized point of responsibility. How does the utility maintain grid manageability and stability under social media/IoT attack?

In terms of more traditional cyberattack, if transactive controls connect the utility to individual home devices that are also Internet connected, then a connectivity path exits form the internet to the utility. If a premise gateway is used by the utility, connectivity still exists, but now a single point of coupling exists that reduces the threat surface somewhat - this is an argument against having utilities reach into the home or business to coordinate or control devices.

Protection is largely component-based, non-adaptive, and requires detailed ad hoc knowledge and constant adjustment. Digital relays require many complicated settings and adjustments. No methods exist to derive settings automatically or even systematically and changing settings in real time to reflect changing circuit topology or system conditions is largely a theoretical concept. Protective relaying covering components, zones, areas (Remedial action Schemes, RAS) and systems (System Integrity Protection System, SIPS) requires setting large numbers of complicated relay parameters using mostly ad hoc approaches to protection coordination.

Several protection and control functions for grids are based in instantaneous frequency (IF) or instantaneous rate of change of frequency (RoCoF). However, the methods used do not measure either of these properly.

Existing methods make measurements over significant time windows, thus computing average values rather than instantaneous values. This reduces the accuracy of PMU measurements, for example, and leads to errors where IF is used in protection. For RoCoF, the inability to compute accurate values hampers the implementation of some microgrid islanding protective schemes and will limit the ability to create virtual inertia from storage and other inverter-based devices.

Emerging instrumentation such as synchrophasor measurement is not employed although the potential is recognized. Closing the loop in a structured way for protection at the local, zone, area, system, and backup levels is needed. Manual setting and adjustment of relay settings must be eliminated or reduced to automation.

3.7 Communications and Data: Inadequate Connectivity and Systematic Data Management

Licensing and availability of spectrum for utility operational communications is limited by the ability of telecom companies to bid up and acquire spectrum licenses in bands that would be useful to the utilities.

Police/fire/EMS groups have fought the utilities vigorously and successfully at the FCC and Congressional levels to keep utilities from getting dedicated spectrum and from getting 'first responder" status on existing wireless networks. The telco's have also fought utility dedicated spectrum successfully because they want to force the utilities to use the telco networks. The utilities have had two objections: they need first responder status, and they have security requirements that may include NERC CIP. However, NERC CIP explicitly excludes telco networks from requirements if the utilities use VPN, IPSEC or other security measures for data in transit across telco networks. The other argument utilities use is that telco base stations do not have adequate battery backup for outage situations and therefore are insufficiently resilient. This issue and access are resolvable via SLA’s, but the telco's have tended to try to gouge the utilities for such agreements.

Much of this could be resolved within 1 or 2 generations of technology development around software defined radios (SDR). SDR technology with enough intelligence could eliminate the need for dedicated spectrum entirely through auto configuration of band, modulation technique, etc. The present spectrum allocation/licensing situation tends to inhibit SDR, so it is developing in the context of Wi-Fi, Zigbee, etc.

Field Area Networks (FANs) provide "last mile" communications for many US AMI systems and are proposed for new Distribution Automation communications. Wireless mesh FANs, and wireless FANs in general, have issues and limitations that make them problematic for mission-critical grid control systems.

Wireless mesh networks suffer severe performance limitations due to several factors: limited bandwidth, internal administrative traffic using much of the available raw bandwidth to keep the mesh in operation, large latencies due to packet hopping, extensive packet loss, limited protocol availability, scalability problems, and very long delays in mesh reformation after an outage.

With the proliferation of deployments, the data identifiers and system state are difficult to correlate and manage without systematic data management strategies. Insufficient meta-data management across organization boundaries leads to additional data management complexity and interoperability barriers.

3.8 Operation and Planning: Market Complexities may Introduce Instability

Driven by issues listed above such as proliferating grid structures, difficulty of control and dispatch schemes, load and generation stochasticity, and deteriorating data interoperability, market signals may not be managed effectively. This could lead to arbitrage and arrangements created by lack of proper grid visibility, leading ultimately to grid instability.

Benefits related to grid investments often accrue to parties or industry segments other than those who would make the investments and so investment is held back. This issue is driven in part by emerging trends in industry structure and partly in the regulatory structures evolution.

The market complexities can appear in short term trading and also in longer-term planning constructs. This could manifest itself as a resource adequacy systemic issue in the grid due to restructured (and restructuring) markets leading further to patchwork responses, and then further to an unstable set of market structures for extended durations of time.

4.0 Conclusion

The utility industry is undergoing a transition from simply operating efficiently with a high degree of reliability, to keeping the lights on while being resilient, flexible, and agile to new requirements, clean and sustainable, economical, and cyber-physically secure. This change has added mounting complexity, e.g., grid volatility, grid structure change, fast system dynamics, more endpoints, and data, on top of aging infrastructure and legacy structure, hence increasing risk to policy and investment decisions. Methods and tools are needed to help decision makers in the electric industry—such as regulators, utilities, and technology developers—manage this complexity as well as identify hidden interactions and technical gaps that could result in unintended consequences, limited benefit realization, or stranded electricity investments as changes are made to modernize the grid.

Encompassing the disciplines of system architecture, network theory, and control theory applied to the power grid, the process of grid architecture construction results in the highest-level description of the complete grid. The architecture forms a key tool to help understand and define the many complex interactions that exist in present and future grids [62,63]. Not only helping manage complexity (and therefore risk), but grid architecture can also assist communication among stakeholders around a shared vision of the future grid, identify and remove barriers and define essential limits, identify gaps in theory, technology, organization, and regulation, and provide a framework for complex grid-related development activities. The new grid architecture discipline aims to addressing this challenge and making the complex problem manageable with a set of new architecture descriptions and associated tools that will be vital to helping stakeholders assess situations surrounding grid modernization.

The grid architecture development follows the process as illustrated in Fig. 8, which takes the inputs of requirements and constraints, architecture principles and basis, existing grid models, emerging trends, systemic issues, and use cases; defines grid qualities and properties; specifies structures and components as well as their properties; and builds mapping from structures/components to properties and to qualities.

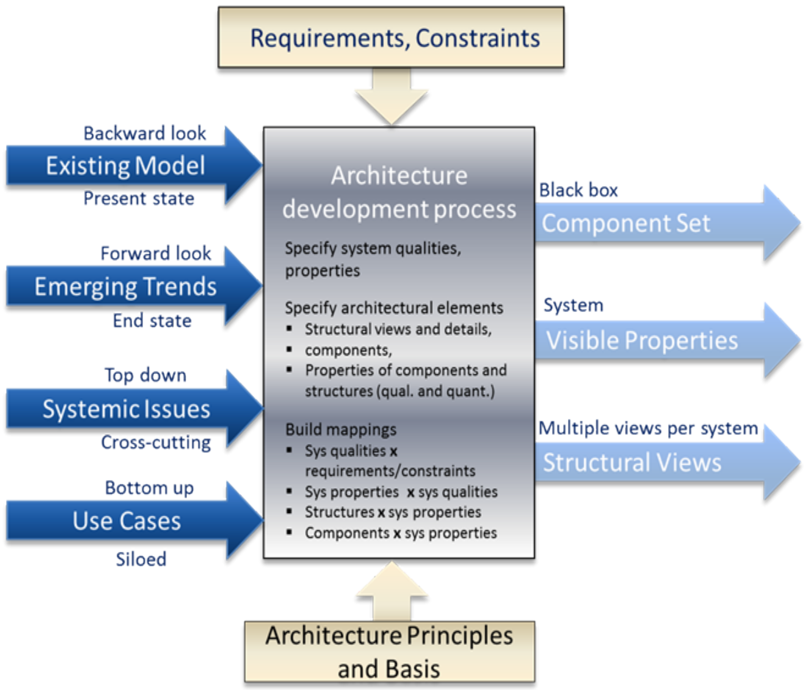

Fig. 8. Grid architecture development process [19,20].

This document provides a thorough listing of the emerging trends and systemic issues extant in power grids and provides input information for the grid architecture development as part of foundational and core activities under US DOE's Grid Modernization Initiative.

Reference

[1] Quadrennial Energy Review, Energy Transmission, Storage, and Distribution Infrastructure, U.S. Department of Energy, April 2015. Available: https://www.energy.gov/sites/prod/files/2016/12/f34/QER%201.1%20Implementation%20Report%20Card.pdf

[2] R. K. Knake, "A cyberattack on the U.S. power grid," Contingency Planning Memorandum No. 31, April 2017.

[3] C. S. Holling, "Resilience and stability of ecological systems," Annual Review of Ecology and Systematics, vol. 4, pp. 1-23, 1973.

[4] NERC, Reliability Concepts, 2007. Available: https://www.pdhexpress.com/wp-content/themes/pdhexpress/pdf-courses/electronic-power-reliability.pdf

[5] National Infrastructure Advisory Council (NIAC), "Critical infrastructure resilience – final report and recommendations," September 8, 2009. Available:https://www.cisa.gov/sites/default/files/publications/niac-critical-infrastructure-resilience-final-report-09-08-09-508.pdf

[6] The White House, "Presidential Policy Directive – Critical Infrastructure Security and Resilience," Feb. 12, 2013. Available: https://obamawhitehouse.archives.gov/the-press-office/2013/02/12/presidential-policy-directive-critical-infrastructure-security-and-resil

[7] IEEE PES Industry Technical Support Task Force: 'The definition and quantification of resilience'. IEEE, 2018. Available: https://grouper.ieee.org/groups/transformers/subcommittees/distr/C57.167/F18-Definition&QuantificationOfResilience.pdf

[8] M. Panteli and P. Mancarella, "Modeling and evaluating the resilience of critical electrical power infrastructure to extreme weather events," IEEE Systems Journal, 2017, vol. 11, no. 3, pp. 1733-1742.

[9] F. Hanif, V. Widiputra, and J. Jung, "State-of-the-art review on power grid resilience to extreme weather events: definitions, frameworks, quantitative assessment methodologies, and enhancement strategies," Appl. Energy, 2019, vol. 239, pp. 1049–1065.

[10] A. Gholami, S. Member, T. Shekari, et al., "Toward a consensus on the definition and taxonomy of power system resilience," IEEE Access, 2018, vol. 6, pp. 32035–32053.

[11] G. Liu, M. Chinthavali, N. Stenvig, X. Li, T. Jiang, Y. Zhang, and K. Tomsovic, "Resilient Microgrid Scheduling Considering Multi-Level Load Priorities," Proceedings of the 2020 IEEE PES General Meeting, Montreal. Canada, Aug 2-6, 2020.

[12] G. Liu, T. Jiang, T. Ollis, X. Li, F. Li, and K. Tomsovic, "Resilient Distribution System Leveraging Distributed Generation and Microgrids: A Review," IET Energy System Integration, vol. 2, no. 4, Dec. 2020, pp. 289-304.

[13] P. Baran, "On distributed communications networks," IEEE Trans. Comm. Systems, vol. 12, no. 1, pp. 1-9, Mar. 1964.

[14] US Department of Energy (DOE), Energy Sector Control Systems Working Group, "Roadmap to Achieve Energy Delivery Systems Cybersecurity," September 2011. Available: https://www.energy.gov/sites/prod/files/Energy%20Delivery%20Systems%20Cybersecurity%20Roadmap_finalweb.pdf

[15] US Department of Energy (DOE), Office of Cybersecurity, Energy Security, and Emergency Response, "Game-changing RD&D to develop resilient energy delivery

systems," Available: https://www.energy.gov/ceser/activities/cybersecurity-critical-energy-infrastructure/cybersecurity-research-development-and
[16] United States Government Accountability Office, Report to Congressional Requesters, "Electricity Grid Cybersecurity" March 2021, Available: https://www.gao.gov/assets/gao-21-81.pdf
[17] R. Black, K. Cullen, B. Fay, T. Hale, J. Lang, S. Mahmood, and S.M. Smith, "Taking Stock: A global assessment of net zero targets, Energy & Climate Intelligence Unit and Oxford Net Zero", March 2021, Available: https://ca1-eci.edcdn.com/reports/ECIU-Oxford_Taking_Stock.pdf
[18] "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, April 22, 2021.
[19] F. Guerra, J. Omar, B. Sergi, M. Craig, P. Michael, A. Kwabena, C. Brancucci, B. Hodge, and R. Sopgwi, "Electric Power Grid and Natural Gas Network Operations and Coordination," United States. 2020. Available: https://www.osti.gov/servlets/purl/1665862.
[20] H. Fan, Q. Yuan, S. Xia, J. Lu and Z. Li, "Optimally Coordinated Expansion Planning of Coupled Electricity, Heat and Natural Gas Infrastructure for Multi-Energy System," IEEE Access, vol. 8, pp. 91139-91149, 2020.
[21] Y. Lin, and Z. Bie, "Study on the resilience of the integrated energy system," Energy Procedia, vol. 103, no. 1, 171–176, 2016.
[22] M. Yan, Y. He, M. Shahidehpour, X. Ai, Z. Li and J. Wen. "Coordinated regional-district operation of integrated energy systems for resilience enhancement in natural disasters" IEEE Transactions on Smart Grid, vol. 10, no. 5, 4881–4892, 2018.
[23] J.D. Taft, and A.S. Becker-Dippmann, "The Emerging Interdependence of the Electric Power Grid & Information and Communication Technology," United States. 2015. Available: https://www.osti.gov/servlets/purl/1221500.
[24] "A National Roadmap for Grid-Interactive Efficient Buildings" U.S. DOE Building Technologies Office, May 2021. Available: https://gebroadmap.lbl.gov/A%20National%20Roadmap%20for%20GEBs%20-%20Final.pdf
[25] NIST Framework and Roadmap for Smart Grid Interoperability Standards, Release 3.0, October 2014. Available: https://nvlpubs.nist.gov/nistpubs/SpecialPublications/NIST.SP.1108r3.pdf
[26] E. K. Lee, R. Gadh and M. Gerla, "Energy Service Interface: Accessing to Customer Energy Resources for Smart Grid Interoperation," IEEE Journal on Selected Areas in Communications, vol. 31, no. 7, pp. 1195-1204, July 2013.
[27] D. Gohlke and Y. Zhou, "Assessment of Light-Duty Plug-In Electric Vehicles in the United States, 2010–2018," United States, January 2019. Available: https://www.osti.gov/servlets/purl/1506474.
[28] A. Cooper and K. Schefter, "Electric Vehicle Sales Forecast and the charging infrastructure required through 2030," Nov. 2018. Available: https://www.edisonfoundation.net/-/media/Files/IEI/publications/IEI_EEI-EV-Forecast-Report_Nov2018.ashx
[29] G. Liu, M. S. Chinthavali, S. Debnath and K. Tomsovic, "Optimal Sizing of an Electric Vehicle Charging Station with Integration of PV and Energy Storage," 2021 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2021, pp. 1-5.

[30] I. Maze-Rothstein "U.S. Microgrid Developer Landscape 2019: Market Shares and Competitive Strategies." January 2020. Available: https://www.woodmac.com/our-expertise/focus/Power--Renewables/us-microgrid-developer-landscape-2019/?utm_source=gtm&utm_medium=article&utm_campaign=wmpr_microgriddev19
[31] M. O'Malley et al., "Enabling Power System Transformation Globally: A System Operator Research Agenda for Bulk Power System Issues," IEEE Power and Energy Magazine, vol. 19, no. 6, pp. 45-55, Nov.-Dec. 2021.
[32] U.S. Energy Information Administration, Annual Electric Generator Report and Preliminary Monthly Electric Generator Inventory, August 2020. Available: https://www.eia.gov/todayinenergy/detail.php?id=44636
[33] U.S. Energy Information Administration (EIA) (2021) Form EIA-860. Available: https://www.eia.gov/electricity/data/eia860/
[34] U.S. EIA (2021) Electric Power Monthly July 2021. Available: https://www.eia.gov/electricity/
[35] U.S. DOE (2021) "Global Energy Storage Database Projects." Available: https://www.sandia.gov/ess-ssl/global-energy-storage-database/
[36] Y. Xue et al., "Towards next generation photovoltaic inverters," Proc. of IEEE ECCE, Phoenix, AZ, 2011, pp. 2467-2474.
[37] Y. Xue et al., "On a Future for Smart Inverters with Integrated System Functions," Proc. IEEE PEDG, Charlotte, NC, USA, June 25-28, 2018, pp. 1-7.
[38] J. Matevosyan et al., "A Future with Inverter-Based Resources: Finding Strength From Traditional Weakness," IEEE Power and Energy Magazine, vol. 19, no. 6, pp. 18-28, Nov.-Dec. 2021.
[39] United States distributed energy resources outlook: DER installations and forecasts 2016-2025E, Wood Mackenzie, June 2020.
[40] "IEEE Standard Conformance Test Procedures for Equipment Interconnecting Distributed Energy Resources with Electric Power Systems and Associated Interfaces," in IEEE Std 1547.1-2020, pp.1-282, 21 May 2020.
[41] FERC, 2020Assessment of Demand Response and Advanced Metering. December 2020. Available: https://cms.ferc.gov/sites/default/files/2020-12/2020%20Assessment%20of%20Demand%20Response%20and%20Advanced%20Metering_December%202020.pdf
[42] Smart Electric Power Alliance (SEPA), Preparing for an Electric Vehicle Future: How Utilities Can Succeed, October 2019.
[43] O. Ceylan, G. Liu and K. Tomsovic, "Coordinated Distribution Network Control of Tap Changer Transformers, Capacitors and PV Inverters," Electrical Engineering, vol. 100, no. 2, June 2018, pp. 1133-1146.
[44] G. Liu and K. Tomsovic, "A Full Demand Response Model in Co-Optimized Energy and Reserve Market," Electric Power Systems Research, vol. 111, Jun. 2014, pp. 62–70.
[45] G. Liu, Y. Xue, M. S. Chinthavali and K. Tomsovic, "Optimal Sizing of PV and Energy Storage in an Electric Vehicle Extreme Fast Charging Station," 2020 IEEE PES Innovative Smart Grid Technologies Conference (ISGT), Washington, DC, USA, 2020, pp. 1-5
[46] G. Liu, T. Jiang, T. Ollis, X. Zhang and K. Tomsovic, "Distributed energy management for community microgrids considering network operational constraints and building thermal dynamics," Applied Energy, vol. 239, Apr. 2019, pp. 83-95.

[47] G. Liu, R. S. Moorthy, J. Choi, M. S. Chinthavali and K. Tomsovic, "Coordinated Optimization and Control of Residential Solid State Power Substations in Electrical Distribution Network," 2021 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT), 2021, pp. 1-5.
[48] G. Liu, R.S. Moorthy, J. Choi, and M.S. Chinthavali, "Linearized three-phase optimal power flow for coordinated optimisation of residential solid-state power substations," IET Energy System Integration, vol.3, no. 3, pp. 344-354, Sep. 2021
[49] "IEEE Standard Profile for Use of IEEE 1588 Precision Time Protocol in Power System Applications," IEEE Std C37.238-2017 (Revision of IEEE Std C37.238-2011), pp.1-42, 19 June 2017.
[50] J. Duan et al., "Deep-Reinforcement-Learning-Based Autonomous Voltage Control for Power Grid Operations," IEEE Transactions on Power Systems, vol. 35, no. 1, pp. 814-817, Jan. 2020.
[51] G. Liu and K. Tomsovic, "Quantifying Spinning Reserve in Systems with Significant Wind Power Penetration," IEEE Transactions on Power Systems, Vol. 27, No. 4, Nov. 2012, pp. 2385 - 2393.
[52] G. Liu and K. Tomsovic, "Robust Unit Commitment Considering Uncertain Demand Response," Electric Power Systems Research, vol. 119, Feb. 2015, pp. 126-137.
[53] Western Energy Imbalance Market Available: https://www.westerneim.com/Pages/About/default.aspx
[54] M. Z. Liu et al., "Grid and Market Services From the Edge: Using Operating Envelopes to Unlock Network-Aware Bottom-Up Flexibility," IEEE Power and Energy Magazine, vol. 19, no. 4, pp. 52-62, July-Aug. 2021.
[55] Michael Hogan, "Follow the missing money: Ensuring reliability at least cost to consumers in the transition to a low-carbon power system," The Electricity Journal, vol. 30, no. 1, 2017, pp. 55-61.
[56] Value Stacking, Available: https://microgridknowledge.com/value-stack-crediting-distributed-energy/
[57] E. O'Shaughnessy, J. Heeter, J. Gattaciecca, J. Sauer, K. Trumbull, and E. Chen, " Community Choice Aggregation: Challenges, Opportunities, and Impacts on Renewable Energy Markets," Golden, CO, National Renewable Energy Laboratory. NREL/TP-6A20-72195. 2019. Available: https://www.nrel.gov/docs/fy19osti/72195.pdf.
[58] Executive Order of the President, "Council of economic advisers, economic benefits of increasing electric grid resilience to weather outages," The Council, 2013. Available: https://www.energy.gov/sites/prod/files/2013/08/f2/Grid%20Resiliency%20Report_FINAL.pdf
[59] A. Kenward, and U. Raja, "Blackout: extreme weather, climate change and power outages," Princeton, NJ, 2014. Available: https://assets.climatecentral.org/pdfs/PowerOutages.pdf
[60] C. T. M. Clack, A. Choukulkar, B. Coté, and S. McKee, "Transmission insights from 'ZeroByFifty'," presented at the Energy Systems Integration Group Transmission Workshop, Nov. 11, 2020. Available: https://www.vibrantcleanenergy.com/wp-content/uploads/2020/11/ESIG_VCE_11112020.pdf
[61] P. Brown and A. Botterud, "The value of inter-regional coordination and transmission in decarbonizing the US electricity system," Joule, vol. 5, no. 1, pp. 115 –134, 2020.
[62] J.D. Taft and A. Becker-Dippmann, "Grid Architecture 1," Technical Report, PNNL-24044, Jan. 2015.

[63] J.D. Taft, "Grid Architecture 2," Technical Report, PNNL-24044-2, Jan. 2016.

GRID MODERNIZATION LABORATORY CONSORTIUM
U.S. Department of Energy

One Bethel Valley Road
P.O. Box 2008
Oak Ridge, TN 37831
(865) 241-1916

http://gridmodernization.labworks.org/