NARUC

National Association of Regulatory Utility Commissioners

Digitalization in Electric Power Systems and Regulation: A Primer

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Contents

Acknowledgments and Disclaimers 1

I. Introduction and Background 3

II. Definition and Technologies 6

What Is Digitalization? 6

Technologies 8

III. Implications of Digitalization 10

Changing Capabilities and Functionality of Power Systems 10

Implications for Grid Architecture 12

Implications for the Utility Business Model 17

IV. Illustrative Examples 20

Automation 20

Virtual Power Plant 21

Transactive Energy 23

Transactive Energy: DSO + T 26

Substation Automation and Virtualization 26

V. Conclusions and Action Steps for Commissions 27

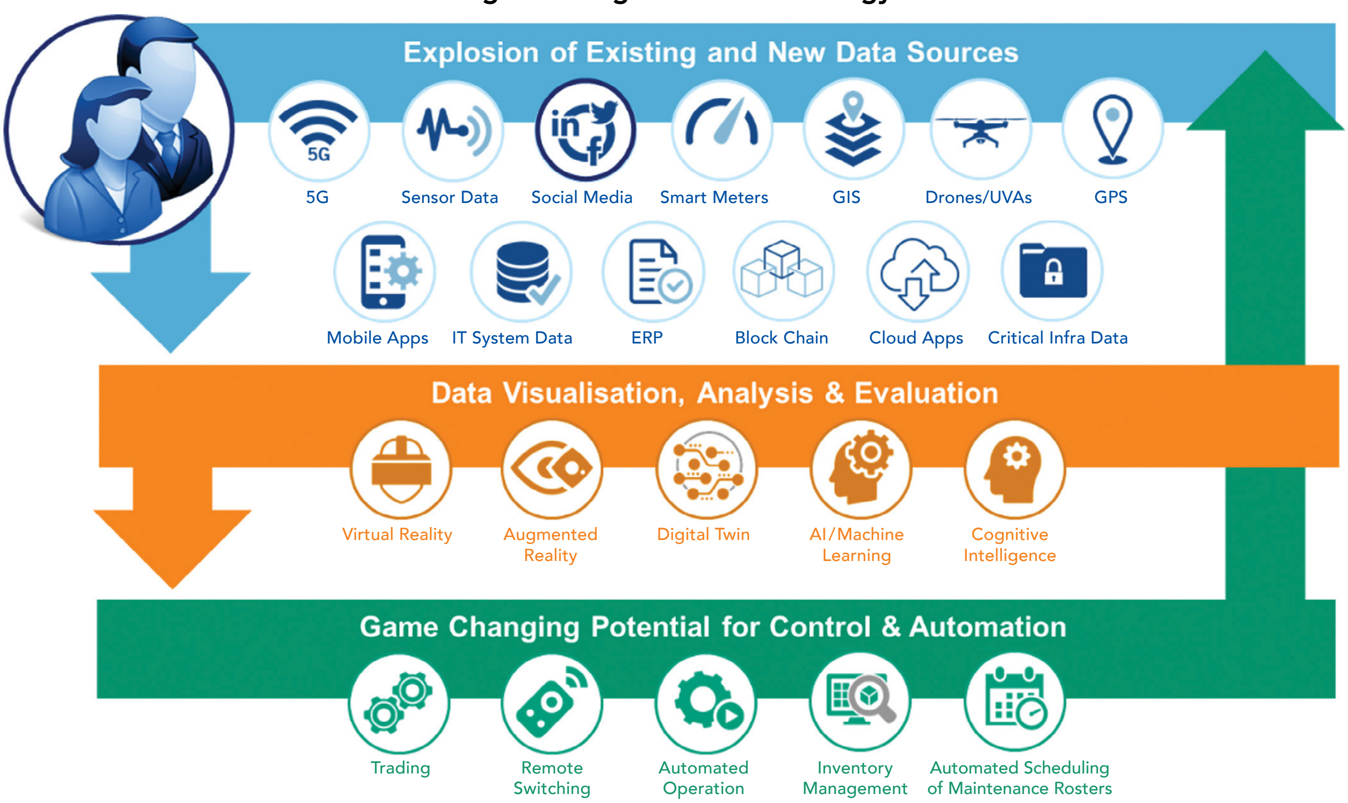
Actions Commissions Can Take 28

I. Introduction and Background

The economy has been digitizing (i.e., incorporating digital communications and control) for more than three decades. A digital economy has led to the emergence of more interconnection and automation, with myriad benefits that were unimaginable 30 years ago: more choice through more extensive markets, greater flexibility and convenience, an increased range of products and services, and more product differentiation to meet diverse preferences. Digitalization has decreased transaction costs: the search, data replication, communications, tracking, and verification costs that have otherwise slowed or prevented mutually beneficial exchange from occurring.[1] Automation decreases the cost of performing repetitive actions and responding to new information, freeing up human time and attention for other activities. Digitalization has also created new data sources and new analytical tools. In 2020, the International Data Corporation projected that 65 percent of global economic activity would be digitalized by 2022, and that investments in digitalization between 2020 and 2023 would total $6.8 trillion.[2]

The combination of digitalization and distributed energy resources (DER) innovations has considerable implications for utility regulators. Many states are experiencing substantial DER investment and the forecast growth of electric vehicles (EVs), as well as new renewables coming on to the bulk power system. These evolutions will create both opportunities and challenges for Public Utility Commissions (PUCs) that oversee distribution (and in some states, transmission) system planning and perform traditional economic regulation functions while also mapping out clean energy transition pathways and implementing state clean energy requirements.

Figure 1. Digitalization of Energy



Source: Mostyn Brown, Stephen Woodhouse, and Fereidoon Sioshansi, "Digitalization of Energy," in *Consumer, Prosumer, Prosumager: How Service Innovations Will Disrupt the Utility Business Model*, ed. F.P. Sioshansi (Academic Press, 2019), 3–25.

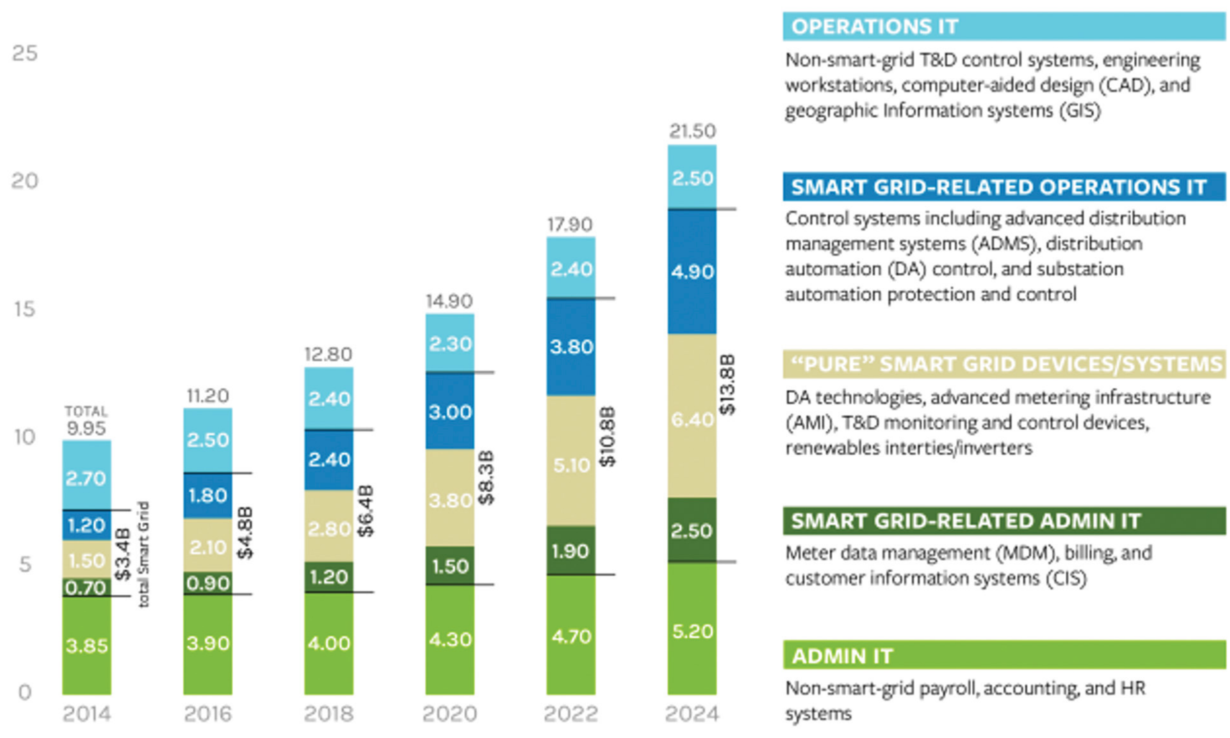
1 Shane Greenstein, "The Economics of Digitization." *The Reporter* (National Bureau of Economic Research, July 2020), https://www.nber.org/reporter/2020number2/economics-digitization. Greenstein also reports that the number of new products tripled between 2000 and 2008.

2 International Data Corporation, "IDC FutureScape: Worldwide Digital Transformation 2021 Predictions" (Doc # US46880818, October 2020), https://www.idc.com/getdoc.jsp?containerId=US46880818&pageType=PRINTFRIENDLY.

The role of PUCs is to attempt to align utility investment plans with a definition of the broader public interest. To the extent that cost-effective decarbonization is in the public interest, digitalization is a primary enabler of decarbonization by facilitating DER interconnection, visible and beneficial operations, and market transactions. Embracing digitalization, changes to grid architecture, and new approaches and business models can make the transition more streamlined and more efficient with fewer transaction costs, and lower costs. Understanding what these changes imply for grid architecture at a conceptual level, as discussed in this report, is essential for decision making about utility investments to enable cost-effective transition.

Digitalization has started to affect the electricity industry over the past 15 years, later than other industries. The growth of smart grid design and investments and grid modernization indicates the impact of the growing convergence of information technology (IT) and operations technology (OT) systems, as illustrated in **Figure 1**. These changes complement the earlier development of Supervisory Control and Data Acquisition (SCADA) systems and other digital technologies implemented in control rooms for both the bulk power and distribution systems, as represented in **Figure 2.** The increase in digital devices around the edge of the distribution network (the "grid edge") enhances decentralization and empowers consumers to control and manage their energy consumption, and increasingly, their production, including the use of automation through a variety of digital devices (from smartphones to digital photovoltaic (PV) system inverters) to increase their convenience and flexibility. The combination of these changes has created the potential to reduce utility costs while also enabling new and convenient customer value propositions.

Figure 2. Digitalization in Distribution Systems



Source: U.S. Department of Energy, Smart Grid System Report (November 2018), Figure 4, https://www.energy.gov/sites/prod/files/2019/02/f59/Smart%20Grid%20System%20Report%20November%202018_1.pdf.

The past decade has seen further changes in the electric system, in the form of variable renewable energy (VRE) and DER. Production costs of these resources, most notably onshore wind and solar PV technologies, have fallen to the point of being competitive with traditional fossil fuel technologies. Battery storage costs are also falling, increasing technological heterogeneity and diversity, and changing the operational, economic, and environmental profile of the resource mix. These changes have accompanied, and in many cases have been spurred on by, federal, state, and local policy actions designed to decrease the environmental impact of energy systems. VRE and DER more generally can yield considerable economic and environmental benefits, but doing so requires reconsideration of grid operations in the pursuit of a distribution grid that is simultaneously safe, reliable, resilient, affordable, and "clean."

Digitalization can help deliver the benefits of decentralization and decarbonization while mitigating some of their challenges. Remote sensors and controls, automation, networks, and digital market platforms enhance flexibility and enable scheduling of demand to coordinate with supply, rather than the traditional practice of scheduling supply to meet inflexible demand. By decreasing transaction costs that can prevent widespread market participation, digitalization makes possible the use of effective decentralized grid management approaches, including microgrids, dynamic pricing, and transactive energy. This report defines grid digitalization, provides concrete examples, and assesses five elements of digital systems that have evolved over the past three decades relevant to the electric distribution system:

- network interconnection,
- interoperability,
- modularity,
- open source, and
- automation.

This report also discusses the benefits and challenges of digitalization and provides a set of actions regulators can take to support the transition and realize the benefits of the transition.

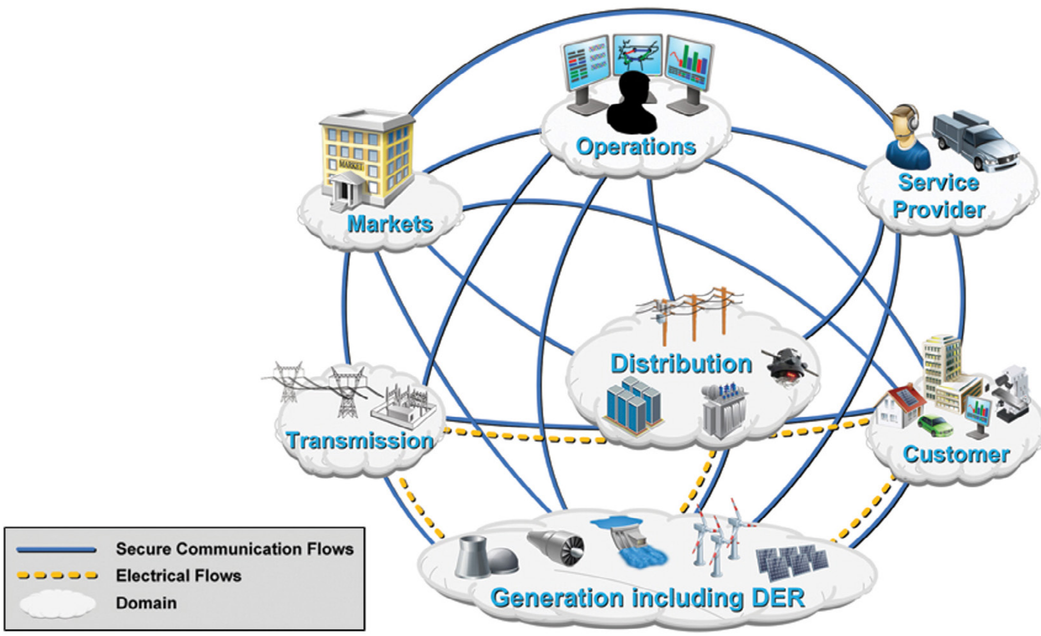
II. Definition and Technologies

What Is Digitalization?

The definition of electric system digitalization begins with the smart grid concept that has been developing over the past 15 years. The National Institute of Standards and Technology (NIST) defines smart grid as "a modernized grid that enables bidirectional flows of energy and uses two-way communication and control capabilities that will lead to an array of new functionalities and applications."[3] The smart grid concept encompasses several different dimensions of digitizing the electric system, all grounded in the basic concept of a communications network overlay on the power system (**Figure 3**). When integrated with the power system, the various technologies and institutions that comprise this communication system create new capabilities with both economic and environmental implications. Digitalization also incorporates the related ideas that have developed in grid modernization.[4]

In its 2017 report on energy system digitalization, the International Energy Agency defined digitalization as "the increased interaction and convergence between the digital and physical worlds."[5] In electric systems in the United States, this interaction began in the 1970s with the development of SCADA systems for managing and operating grids. Since that time, control rooms have become increasingly digital, with expanded data visualization, data analytics to enhance real-time operations, and connectivity across regions to enhance coordination.

Figure 3. The National Institute of Standards and Technology Smart Grid Model



Source: NIST Smart Grid Frmework 4.0, https://www.nist.gov/system/files/documents/2019/06/06/presentations-day1.pdf

One way to think about electric system digitalization is to think about the grid as a multilayered cyber-physical-social system. For example, a digital thermostat connected to a home's wireless network and to a mobile device app uses a communication network and the internet (cyber) to enable remote control and automation of a device that connects to the distribution system (physical), to enact individual choices and meet human needs through transactions (social). The grid is layered in the sense that these different systems interact but are

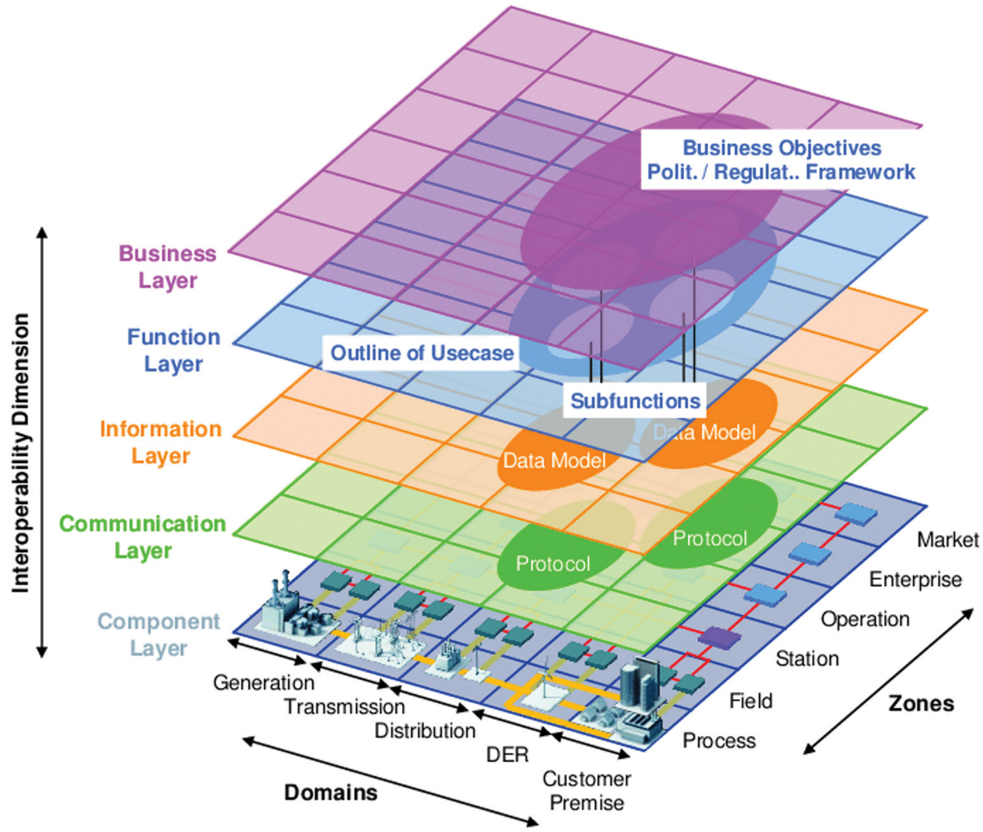
3 National Institute of Standards and Technology, *Smart Grid Beginners Guide*, https://www.nist.gov/el/smart-grid/about-smart-grid/smart-grid-beginners-guide.

4 See, for example, the work of the Grid Modernization Laboratory Consortium at https://gmlc.doe.gov.

5 International Energy Agency, *Digitalization and Energy* (2017), 21, https://www.iea.org/reports/digitalisation-and-energy.

also different categories of technologies or functions. The Smart Grid Architecture Model (SGAM), depicted in **Figure 4**, illustrates this framework.[6]

Figure 4. The Smart Grid Architecture Model



Source: Dänekas et al., "Towards a Model-Driven-Architecture Process for Smart Grid Projects," Figure 1.

Cyber-physical systems "integrate sensing, computation, control, and networking into physical objects and infrastructure, connecting them to the internet and to each other."[7] Cyber-physical-social systems expand the definition to include integration of humans and our social systems into the connections with mechanical systems and digital information systems, taking into account human factors in the design of cyber-physical systems and including human organizations and institutions in analysis and design.[8]

At its foundation, a digital electric grid remains a mechanical power network, with interconnected technologies for generation, transmission, distribution, voltage and frequency control, and connection to end uses inside individual premises. Physical rules and architectural decisions determine how these technologies interconnect, interoperate, and are managed. These operations occur within organizations: investor-owned, cooperative, or municipal/public electric utilities. On top of this physical power system layer, a communications or information technology layer connects to the power system. This new informational capability of a digital electric system makes the physical system visible and controllable in different ways than were the case in the previous electro-mechanical system.

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6 Christian Dänekas, Christian Neureiter, Sebastian Rohjans, Mathias Uslar, and Dominik Engel, "Towards a Model-Driven-Architecture Process for Smart Grid Projects," in *Digital Enterprise Design & Management* (2014), 47–58. See also M. Gottschalk, M. Uslar, and C. Delfs, "The Smart Grid Architecture Model—SGAM," in *The Use Case and Smart Grid Architecture Model Approach* (SpringerBriefs in Energy, 2017), https://doi.org/10.1007/978-3-319-49229-2_3.

7 National Science Foundation, "Cyber-Physical Systems," https://www.nsf.gov/news/special_reports/cyber-physical/.

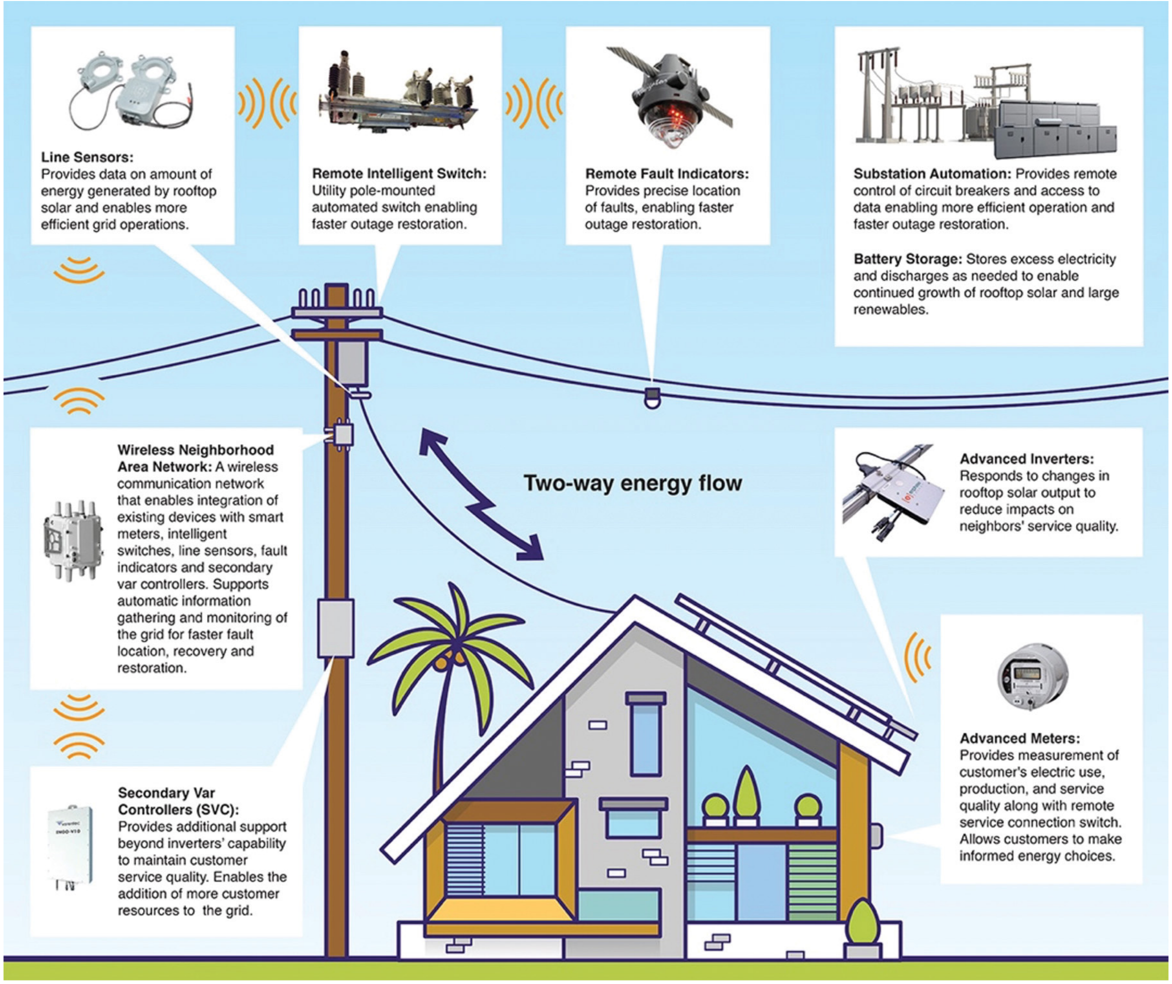
8 For an engineering treatment of cyber-physical-social systems, see Yuchen Zhou, F. Richard Yu, Jian Chen, and Yonghong Kuo, "Cyber-Physical-Social Systems: A State-of-the-Art Survey, Challenges and Opportunities," *IEEE Communications Surveys & Tutorials* 22, no. 1 (2019): 389–425.

The convergence of power systems and communications systems into cyber-physical-social electric systems means that electric grids will be systems of systems. In systems theory, a system of systems is a collection of systems that, when combined, creates a new complex system with different capabilities. An important characteristic of a system of systems is the interdependence between one system and another. Systems can either be tightly coupled, where the components of one system rely specifically on the components of another, or loosely coupled, where the reliance on components of other systems is more generalized. An example of a tightly coupled system is razors and razor blades, because a razor only works with replacement blades designed for that specific razor. In contrast, the internet is the epitome of a loosely coupled system, with an ability to connect, disconnect, and change components and devices while the whole system continues to operate.[9]

Technologies

A wide variety of technologies create and use the digitalized electric system of systems. These technologies include: sensors and controls, phasor measurement units (PMUs) and other distribution automation technologies, drones, devices around the distribution edge (e.g., "Internet of Things" (IoT) devices[10]), artificial intelligence

Figure 5. Distribution System Digitalization in a High-DER Environment



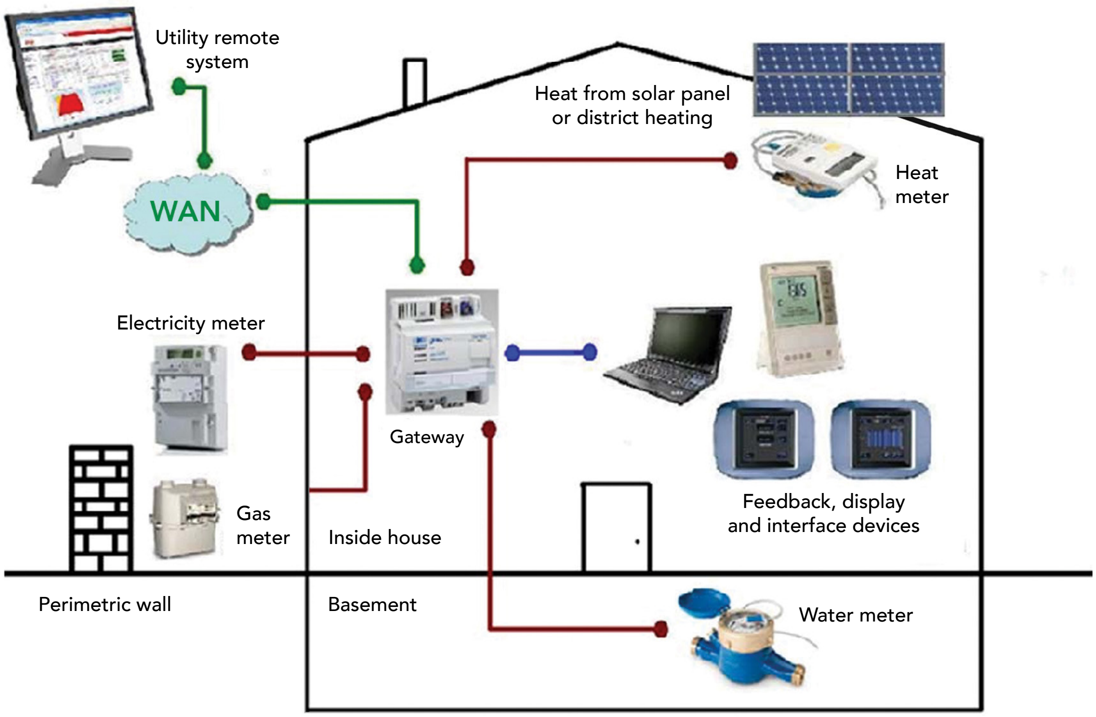
Source: M. Asano, "Grid Modernization in a High DER Environment" (2018 IEEE PES T&D Conference).

9 The Pacific Northwest National Laboratory's Grid Architecture group provides a useful glossary of system terms (e.g., system, components, structure, relationships, architecture) at https://gridarchitecture.pnnl.gov/basic-terms-and-principles.aspx.

10 The IoT describes physical objects (or groups of such objects) with sensors, processing ability, software, and other technologies that connect and exchange data with other devices and systems over the internet or other communications networks. Devices do not need to be connected to the public internet, they only need to be connected to a network and be individually addressable.

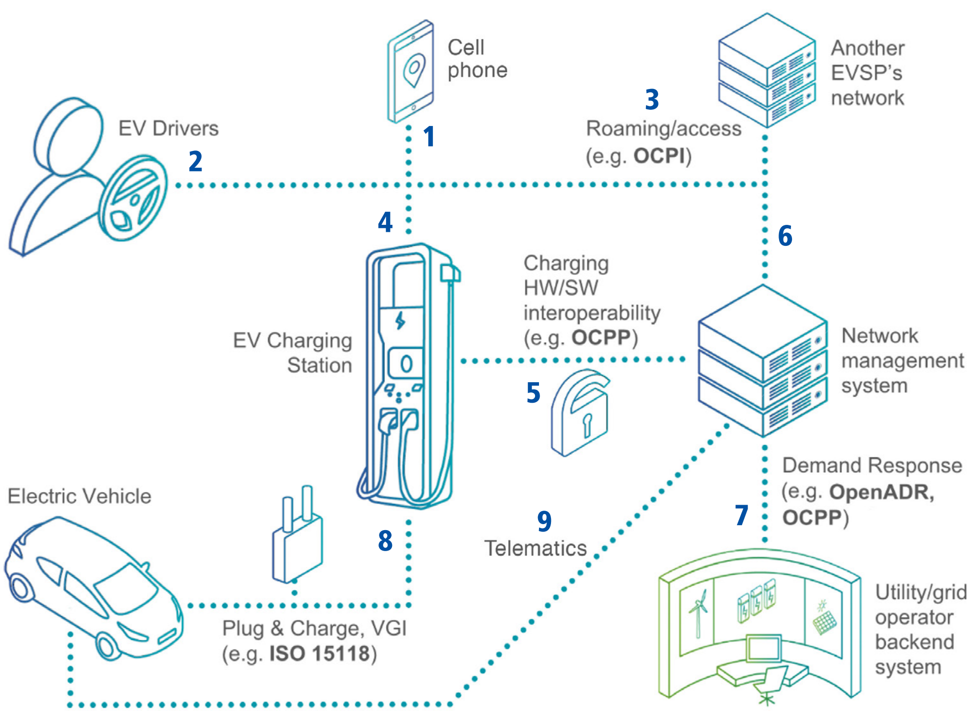
and machine learning, management systems (e.g., DERMS, HEMS, ADMS), blockchain, cloud storage, and software to connect these technologies. **Figures 5**, **6**, and **7** illustrate how these technologies are used to interconnect DER, smart buildings, and EV infrastructure to the distribution system.

Figure 6. Home Digitalization and Energy Management Systems



Source: Norma Anglani, Ezio Bassi, Francesco Benzi, Lucia Frosini, and Tommaso Traino, "Energy Smart Meters Integration in Favor of the End User," *2011 IEEE International Conference on Smart Measurements of Future Grids (SMFG) Proceedings* (2011): 16–21.

Figure 7. Digital Integration of EVs in the Distribution System



Source: Shell Recharge Solutions (formerly Greenlots)

III. Implications of Digitalization

Changing Capabilities and Functionality of Power Systems

Electric system digitalization creates benefits in the form of new capabilities and functionality that the traditional electro-mechanical system did not possess: [11]

- intelligence,
- efficiency,
- motivation,
- flexibility,
- resilience, and
- environmental alignment.

The capabilities examined in this section overlap with those described in the U.S. Department of Energy's smart grid primer:[11]

- Intelligent,
- Efficient,
- Accommodating,
- Motivating,
- Opportunistic,
- Quality-focused,
- Resilient, and
- Green.

The most important, and most general, digitalization capability is intelligence. Interconnected remote digital sensors create visibility and monitoring capabilities out to the edge of the distribution grid, enabling more targeted operational decisions to maintain reliable service. Investing in technologies like PMUs provide such visibility within the distribution grid as well as automated repair capabilities. Digital sensors in substations and transformers illuminate grid conditions as they change in real time. Intelligence within the grid raises operational awareness. One often-cited critique of distribution systems is that end users have had to call the utility to report outages, but digital sensing, monitoring, and repair both alert operators to outages and reduce their likelihood and duration.

Another valuable aspect of digital intelligence is increased intelligence around the distribution edge. Digital sensors and devices make it safer, easier, and cheaper to connect a variety of devices to the distribution grid. Some are connected directly to the grid (e.g., solar PV system inverters), while other "behind the meter" devices increase the convenience and value to end users of using more energy-related digital technologies in their premises. Examples of the latter include smart plugs that can be controlled with a mobile device app or home energy management systems that interconnect the appliances and devices in a home and enable user automation and control. These intelligent distribution edge devices have such potent capabilities because they allow access not just to energy-related devices, but also (and more importantly) because they allow access to end user preferences and knowledge in ways that are impossible in an electro-mechanical distribution grid where consumer preferences are not known. End users can now be empowered to make decisions regarding their energy consumption and production, both to their own benefit and to the benefit of the distribution system by changing the pattern of their energy behavior and even by providing grid services that only the utility used to be able to provide.

This general and pervasive digital intelligence increases the efficiency of the distribution grid. Efficiency means creating the most possible benefit with the fewest possible resources. Traditionally in the vertically integrated, regulated utility, efficiency is defined as the least-cost generation of electricity of a particular quality level and reliability. In a regulated system with fixed rates that reflect average cost, investment is targeted to meeting peak demand as quantity varies, because supply and demand cannot be coordinated by price signals. Those peak-focused resources sit idle most of the time, and over time as population growth and economic growth led to demand growth, more investment occurred in meeting peak demand and in idle resources.[12]

11 U.S. Department of Energy, *Smart Grid: An Introduction*, https://www.energy.gov/sites/default/files/oeprod/DocumentsandMedia/DOE_SG_Book_Single_Pages%281%29.pdf.

12 Moslem Uddin, Mohd Fakhizan Romlie, Mohd Faris Abdullah, Syahirah Abd Halim, and Tan Chia Kwang, "A Review on Peak Load Shaving Strategies," *Renewable and Sustainable Energy Reviews* 82 (2018): 3323–3332.

Digitalization enables a refined approach to efficiency, one that allows for meeting demand (and growing demand) without necessarily adding infrastructure or increasing investment in peak-focused resources. Under this efficiency concept, digitalization creates the capability to expose more end users to time-varying dynamic pricing that reflects actual system conditions and the actual marginal cost of consumption. Simultaneously, digitalization reduces tradeoffs by allowing end users to respond to dynamic pricing without sacrificing comfort or convenience, potentially reducing their electricity bills in the process. They can use devices and software to engage in either remote control of their electricity behavior or automated responses to changing prices. They can implement override rules if their real-time circumstances induce them to deviate from their automated decisions. Digitalization allows end users to choose how they want to make decisions about their electricity behavior, choices that were not possible in an electro-mechanical grid with uniform service offerings.

Efficiency also has a dynamic dimension, meaning that over time as system participants produce, consume, invest, and innovate, they learn the benefits and costs of their decisions and can change their behavior accordingly. The result is generally a closer match of costs and benefits over time—not necessarily falling costs, because the electric system and its participants may be providing more and different benefits due to digitalization and the resulting innovation in technologies, products, services, and organizational forms. Consider the example of mobile phone service, for which customers pay higher prices and receive much more value than when the only option was a landline analog phone with a regulated, cost-based rate. The evolution of the mobile phone shows the importance of focusing on matching costs and benefits rather than on minimizing costs of a single, basic service.

Using digitalization-enabled intelligence to achieve such dynamic efficiency relies on how digitalization affects individual motivation. Digital devices and communications systems enable information provision and sharing that can inform individual incentives and real-time decisions. Real-time communication can take multiple forms, depending on the institutional framework—the regulatory environment and the industry business model. In a vertically integrated setting, commissions can approve tariffs in which the customer chooses a regulated rate that allows the utility to share real-time information and control of their electric equipment (e.g., as a more sophisticated version of air conditioning systems cycling via direct load control). In a competitive retail setting, the customer can choose a contract that allows the retailer similar control rights, or a contract in which the customer faces a market price and uses digital technologies to automate energy decisions based on that price and its changes over time. Similarly, a customer could choose a contract based on environmental considerations and can automate their decisions accordingly.[13] In either a vertically integrated or a competitive setting, digitalization harnesses individual incentives through the use of transactive systems to coordinate supply and demand decisions, through a utility or a retailer, or through a microgrid operator or building control system coordinating supply and demand internally (a topic discussed in more detail in Section 4).

The combination of intelligence and motivation yields flexibility, an essential process for achieving efficiency. Flexibility is the ability of a resource to adapt to changing conditions by changing its behavior. Digitalization enables flexibility through enhanced sensing and monitoring of grid conditions, communicating those conditions and changes in them to participants and their devices around the distribution edge, communicating how those devices are going to adapt to those conditions, and then implementing those decisions either through manual or automated control. In a nondigital distribution grid, participants are unlikely to be aware of changing grid conditions in a way that enables them to change their behavior and their device actions; this lack of distributed intelligence is a primary reason for the crucial role of the centralized control room operator. However, distributed intelligence coupled with an institutional structure that provides incentives to distributed resources and devices to change their behavior can lead to flexibility as some of those distributed

13 The foregoing discussion regarding customer behavior and investment in automation or behavior change does not address the possibility that the evolution of the grid and utility business models may exacerbate issues of equity and the "digital divide." Such considerations are beyond the scope of this paper.

resources adapt. Flexibility is perhaps the most important capability that will enable greater and more efficient decarbonization through making more widespread DER adoption possible. Flexibility is the key to evolving from the 20th century operating paradigm of varying supply to meet demand to a new paradigm of varying demand to meet supply.

These capabilities culminate in an essential modern grid capability: resilience. Resilience is the ability of a system to return to a base state of operation after an event that could cause large area, long-duration outages. A recent report on electric system resilience from the National Academies of Sciences, Engineering, and Medicine focused on identifying ways to increase power system resilience noted that:

> Resilience is not just about lessening the likelihood that these outages will occur. It is also about limiting the scope and impact of outages when they do occur, restoring power rapidly afterwards, and learning from these experiences to better deal with events in the future.[14]

Resilience is thus more than reliability as measured by outage rates and outage duration; it is also more than simply a physical system concept, encompassing the ability of communities and their social networks to reduce hardship and lessen the duration of outages. Distributed digital intelligence, individual motivations and incentives, and flexibility (the previously described characteristics of a digitalized electric system) are essential contributing capabilities to the power system's resilience.

The final capability that digitalization provides is alignment of environmental and economic goals.[15] The combination of intelligence, efficiency, motivation, and flexibility creates a system in which individuals can manage or reduce their energy use to reduce both their bills and their emissions. These individual actions aggregate to larger emission reductions that contribute to meeting policy targets. Another environmental benefit from additional flexibility is how digital sensing and monitoring reduce the magnitude of spinning reserves required for reliability, which reduces emissions. This same digital sensing and monitoring, along with automation, increase the system's ability to integrate and absorb more DER than would be possible otherwise, which moves the fuel mix in a decarbonizing direction.[16]

Implications for Grid Architecture

The digitalization of the electric grid has implications for how we use it, the resources that can connect to it, and even the structure and architecture of the grid itself. Grid architecture applies system theory, network theory, and control engineering to understanding the structure of the grid, its complexity, and how it can change as the nature and capabilities of the resources in the grid change.[17] Using the systems concepts introduced in Section 2, Grid Architecture is an abstract representation of how the different components of a system relate to each other, how they combine to create a system of systems, and what the properties and capabilities of the system are, much like a detailed blueprint for a building. **Figure 8** illustrates the changes digitalization will create in grid architecture.

In the electro-mechanical grid of the 20th century, the structure of the system was unidirectional because of technological characteristics: generation was large scale and in fixed locations, and end users were only

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14 The National Academies of Sciences, Engineering, and Medicine, *Enhancing the Resilience of the Nation's Electricity System* (National Academies Press, 2017), S-1, http://nap.edu/24836.

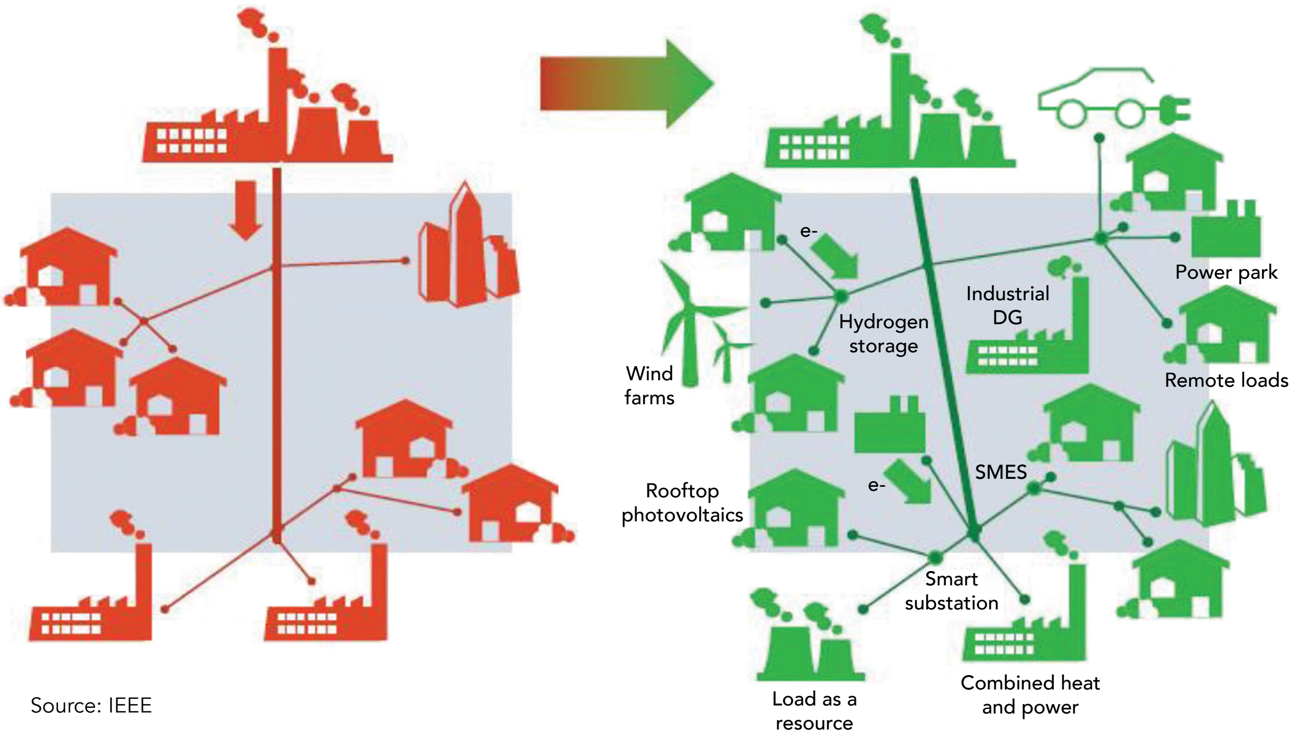
15 For deeper discussion of digitalization for deep decarbonization, see Varun Sivaram, ed., *Digital Decarbonization: Promoting Digital Innovations to Advance Clean Energy Systems* (Council of Foreign Relations, 2018).

16 Nicolò Rosetto and Valerie Reif, "Digitalization of the Electricity Infrastructure: A Key Enabler for the Decarbonization and Decentralization of the Power Sector," in *A Modern Guide to the Digitalization of Infrastructure* (Edward Elgar Publishing, 2021); Jaquelin Cochran, Paul Denholm, Bethany Speer, and Mackay Miller, *Grid Integration and the Carrying Capacity of the US Grid to Incorporate Variable Renewable Energy* (NREL/TP-6A20-62607, National Renewable Energy Laboratory, 2015).

17 For an introduction to electric grid architecture, see Jeffrey D. Taft, "Grid Architecture: A Core Discipline for Grid Modernization," *IEEE Power and Energy Magazine* 17, no. 5 (2019): 18–28. For a deeper grid architecture analysis and framework, see Jeffrey D. Taft and A. Becker-Dippmann, *Grid Architecture* (No. PNL-24044, Pacific Northwest National Laboratory, 2015); and Jeffrey D. Taft, *Grid Architecture 2* (No. PNL-24044-2, Pacific Northwest National Laboratory, 2016).

consumers, not producers. Thus, the grid was designed for one-way flow from generators to consumers. The institutional frameworks of economic regulation and industrial organization (vertically integrated spatial monopoly) were predicated on this system architecture, and the relative homogeneity of the types of component technologies, regulatory rules, and organizational forms limited the complexity of the system.[18] One lasting consequence of this architecture is the centralized engineering control of distribution system operations. The analog control system of the 20th century also had a lack of distributed visibility, requiring actions like customers calling to report outages that were otherwise not visible to the control room operators.

Figure 8. Digitalization's Implications for Grid Architecture



Source: IEEE

Multiple technological forces have put pressure on this existing grid structure over the past 15 years. In contrast to the large scale and the centralizing impetus of last century's technologies, the digital and DER innovations of the 21st century have strong decentralizing forces. These new potential benefits and valuable attributes from decentralization change the desirable grid architecture.

In system of systems terms, technology advancement has changed the nature of the components available for the distribution system and increased their capabilities. These new components combine digital and distributed characteristics and operate at different scales and locations. Microgrids are an example of a new organizational form arising from these new components and combinations. These technical changes have occurred while policy objectives have evolved to include environmental impact and decarbonization, objectives that were not incorporated into infrastructure investment decisions in the electro-mechanical grid of the 20th century. When both the technology components and their capabilities change and the institutional context changes, both the possible and the desirable structure of the distribution system also changes. For these reasons, it is necessary to rethink grid architecture and the structure of the distribution system to take advantage of the economic and environmental benefits of digitalization and DER.

18 Lynne Kiesling, "Implications of Smart Grid Innovation for Organizational Models in Electricity Distribution," in *Wiley Smart Grid Handbook*, ed. Chen-Ching Liu, Stephen McArthur, and Seung-Jae Lee (Wiley, 2016).

In thinking about electric grid structure and architecture, five elements of the digital systems that have evolved over the past three decades are relevant:

- network interconnection,
- interoperability,
- modularity,
- open source, and
- automation.

These elements, explored further below, define the relationships among components and how they can form a system that allows exploitation of their capabilities.

While also a feature of nondigital networks (such as highway, rail, and air networks), *network interconnection* is a fundamental characteristic of digital networks. An interconnection is a physical connection between two separate networks, or between a network and an electronic device. Interconnection creates networks by connecting components to each other. In both digital communications networks and electric networks, interconnection takes the form of a wires network connecting different types of components together. Network interconnection enables the mutual exchange of value for value, through both physical and financial transactions.

In electric systems, interconnection has a long history dating back to contracts for emergency backup in the 1920s. Since the formation of organized wholesale markets in the mid-1990s, interconnection also refers to the planned connection of new resources to the transmission grid and to the markets (the interconnection queue). These historic uses of the concept are compatible with its use in digital networks and will increasingly be applied to the connection of DER to the distribution grid.[19]

When considering the interconnection of components into a system, a logical question to ask is how easily such interconnections can occur, or how interoperable the components of the system are. Think, for example, of what happens when you plug an external storage drive into the USB slot on your computer. The computer's operating system recognizes the external drive and makes it available for your use, connecting that drive with the remainder of the components in your system. The kind of "plug and play" interoperability we see in the USB drive takes time to evolve through trial-and-error experimentation. Interoperability is the general capability of a component to interact and function with other components to form a coherent system, independent of the vendor or creator of the component or system. In technology systems, interoperability is often bolstered by industry standards that emerge through experimentation and become codified through standard-setting processes, often intermediated through standard-setting organizations (SSOs). Standards allow diverse stakeholders to come to consensus and coordinate, enabling modular systems to exist and grow.

In digital communications systems, interoperability also means the ability to exchange and use information while retaining the original meaning and understanding of the information, again independent of vendor or creator.[20] Ensuring interoperability in a system requires focusing on the interfaces between each type of component and the rest of the system. The best way to do that is to standardize components, both hardware and software. The USB storage drive provides a useful example of standard interfaces for both hardware—the plug on the drive and the port on the computer—and the software that delineates how the operating system recognizes what type of device it is, permits it to interconnect, and enables the user to perform

19 For an introduction to U.S. interconnection policy, see NARUC and USAID, *An Introduction to Interconnection Policy in the United States*, https://pubs.naruc.org/pub.cfm?id=5375FAA8-2354-D714-51DB-01C5769A4007.

20 NARUC, in collaboration with NIST, provides Interoperability Learning Modules at https://www.naruc.org/cpi-1/energy-infrastructure-modernization/smart-grid/interoperability-learning-modules/. NIST has provided extensive leadership in developing a Smart Grid Interoperability Framework for various stakeholders to use, with version 4.0 available at https://www.nist.gov/publications/nist-framework-and-roadmap-smart-grid-interoperability-standards-release-40.

desired functions with it. Such standardization-enabled interoperability increases the flexibility and value of the device and the system to the user.

The USB standard is an example of an open standard. Open standards are available to the public and are typically developed, approved, and maintained through collaborative and consensus-based processes. In contrast, proprietary or closed standards are controlled by a single company (think, for example, of how one brand of razor only works with that brand's razor blade cartridges, or how the Apple operating system only runs on Apple hardware). Work on open standards is often coordinated through a SSO; in the case of USB standards, they are organized through the USB Implementors Forum, which counts among its members Intel, HP, Apple, and Microsoft. Other organizations that coordinate standards relevant to power systems include the International Electrotechnical Commission (IEC) and the Institute of Electronics and Electrical Engineers (IEEE). For example, IEC 61850 is an open standard governing digital substation automation, and IEEE 1547 is an open standard governing digital inverters.[21] Adoption of these open standards reduces the transaction costs associated with interconnecting and replacing these devices in power systems and creates certainty around how they will operate within those systems.[22] At the customer level, modularity is a by-product of such standard interfaces. As a general characteristic of systems, modularity is the "degree to which a complex system can be broken apart into subunits (modules), which can be recombined in various ways."[23] Modularity means that different, standard components can substitute easily for each other, making a system more flexible. A good nondigital example of modularity is the evolution of container shipping in the 1960s. Before standardization, shipments were loaded manually and were in packages of widely varying shapes and sizes. The size and shape of modern shipping containers is standardized, making them stackable and substitutable, which enables automation and reduces shipping costs that flow through to lower prices for consumer goods.[24] A good digital example of the interaction between modularity and standard interfaces is the HDMI cable and the various devices that can connect to it—television, computer, tablet, phone—to display video. Modularity and standard interfaces enable the evolution and success of more complex systems. They also enable different scales of operation by combining multiple numbers of a modular component (e.g., a large battery built of multiple identical smaller batteries).[25]

Standardization and modularity lower the barrier to participation in creating the software/code modules that make up the bulk of the digital system. This path has led to the emergence of commercial open-source software, which integrates commercial software development with community development. With open-source software, users and developers can see the underlying code and modify it as they see fit. More people engage with the code, and this community development creates feedback effects for quality control and security as well as developer independence. Code developers can request licenses for others to use their code, but the license primarily identifies ownership, specifies how the user may profit from the code, and defines obligations the developer has to the user. Software with more permissive licenses tends to find greater uses and to be refined by more developers. Open-source software contrasts with proprietary software, under which the developer strictly controls its design and use.

The most notable and widely used open-source software is the Linux operating system. In 1991 a Finnish student, Linus Torvalds, created a version of the kernel (the core code) of the Unix operating system, which

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21 Institute of Electrical and Electronics Engineers Power and Energy Society, *Impact of IEEE 1547 Standard on Smart Inverters and the Applications in Power Systems* (Technical Report PES-TR67.r1, August 2020), https://www.nrel.gov/grid/ieee-standard-1547/assets/pdfs/smart-inverters-applications-in-power-systems.pdf.

22 The National Renewable Energy Laboratory (NREL) provides extensive materials on IEEE 1547, in part to facilitate widespread adoption of the most recent version of the standard by utility commissions and utilities.

23 Carliss Y. Baldwin, "Bottlenecks, Modules and Dynamic Architectural Capabilities," *Harvard Business School Finance Working Paper 15–028* (2015).

24 Marc Levin, *The Box* (Princeton University Press, 2008).

25 For a more extensive discussion of modularity in digital platforms, see Lynne Kiesling, "Plug and Play, Mix and Match: A Capital Systems Theory of Digital Technology Platforms," *The Review of Austrian Economics* 34, no. 1 (2021): 13–32.

he made freely available. He designed this operating system to be independent of the hardware on which it operated (unlike, for example, Microsoft Windows on compatible PCs or the Macintosh operating system on an Apple computer). This flexibility created considerable development opportunities for programmers, who wrote code modules on top of the Linux kernel and over the ensuing years created the Linux operating system. Since the mid-1990s, many developers and companies have contributed code, and the core of the Linux community is a set of trusted coders who have demonstrated their capabilities through useful and reliable contributions to the Linux kernel and the operating system code base. Out of this development community has evolved the Linux Foundation, which manages the process of maintaining the Linux kernel. Today Linux forms the foundation of most enterprise software systems in use globally, including most of the international financial markets and futures exchanges.

The Open Software Initiative (OSI) defines open-source software's main characteristics as:[26]

1. Free Redistribution,
2. Source Code,
3. Derived Works,
4. Integrity of The Author's Source Code,
5. No Discrimination Against Persons or Groups,
6. No Discrimination Against Fields of Endeavor,
7. Distribution of License,
8. License Must Not Be Specific to a Product, and
9. License Must Not Restrict Other Software.
10. License Must Be Technology-Neutral.

One example of commercial software development in this flexible, open-source environment is RedHat. Founded in 1994, RedHat took the constantly evolving community development of the Linux operating system and packaged it into a consistent, stable, easy to use, and accessible software installation. RedHat did not modify the operating system but layered onto it interfaces and other features that made it better suited to use in a business environment. They also provided service and support. RedHat and other commercial Linux developers reduced the costs and increased business confidence in relying on an open-source operating system.

Open-source software's flexibility and large developer community enabled its use to soar in the 1990s; it became a fundamental building block of the explosive growth of the internet and the digital economy in the ensuing decades. It will also be a fundamental building block of electric system digitalization for the same reasons. This transition will be a cultural shift for utilities, who since their late 19th century origins have

"One group working to promulgate open-source software in power systems is Linux Foundation Energy (LF Energy), a project of the Linux Foundation that brings together stakeholders to solve the complex, interconnected problems associated with the decarbonization of energy by using resilient, secure, and flexible open-source software. The digitalization of power systems enables the abstraction of the world's largest machine into composable software defined infrastructure. Digitalization also means that operators can 'network electrons' by orchestrating the metadata about an electron in ways never before possible. Digitalization facilitates a radically energy-efficient future. When every electron counts, renewable and distributed energy provides humanity with the tools to address climate change by decarbonizing the grid, powering the transition to e-mobility, and supporting the urbanization of world populations.

LF Energy leverages transparent, open-source development best practices, along with existing and emerging standards, to efficiently scale, modernize, and digitally transform the power systems sector. By providing frameworks and reference architectures, LF Energy minimizes toil and alleviates pain points such as cybersecurity, interoperability, control, automation, virtualization, flexibility, and the digital orchestration and balancing of supply and demand."[27]

26 https://opensource.org/osd-annotated.

27 https://www.lfenergy.org/why-lfenergy/.

tended to use bespoke, proprietary engineering to build their systems. The modularity, interoperability, open standards, and open-source software that characterize digital systems will change that, but regulators may have to provide the impetus for such changes to overcome utilities' financial motivation to maintain the status quo.

The previous four elements of digitalization—network interconnection, interoperability, modularity, and open-source software—culminate in the final element: automation. Automation means operating the system, including end-user actions, with a minimum of human intervention. Automation enables decision making to occur based on rules, programmed into algorithms, that implement actions under certain conditions. It harnesses digital technologies and networks to reduce the time and the cost associated with implementing actions.

Most digital systems use, and indeed rely on, automation to operate. Doing transactions through a bank ATM (automated teller machine) is an early example of using automation to perform actions that used to require human-to-human interaction. Today many actions in our daily lives rely on automation, from using a rule to filter your email to setting up a recurring "subscribe and save" online order. Even the simple act of programming a digital thermostat to change temperatures at specific times uses automation to make decisions and actions easier and more convenient.

Implications for the Utility Business Model

The previous discussion indicated some of the implications of digitalization for grid operations, grid architecture, and decarbonization through DER integration. Digitalization also has substantial economic consequences, with implications for the utility business model and future regulatory practice.[28]

Digitalization's economic impact starts with its effect on transaction costs, the costs associated with engaging in market transactions.[29] For several decades, we have seen how digitalization has changed what we exchange, how we exchange, and the nature of how firms organize production. From Amazon to Zillow, digitalization has transformed our economy through the five elements discussed in the previous section (interconnection, interoperability, modularity, open-source, and automation).

In his seminal article *The Nature of the Firm*, Ronald Coase developed a model of firms and their structure that depends on transaction costs.[30] If transaction costs are zero, all economic activity can take place through market contracts rather than the hierarchy of a firm. But transaction costs do exist, and firms are organizational structures that enable economically efficient production to occur by economizing on transaction costs. In organizations, people use management, rules, and hierarchy to organize production in situations with high transaction costs. Transaction costs determine the boundary between transactions that are more efficiently accomplished when integrated into firms and transactions that are more efficiently accomplished through market contracts.

Electric service has always been a high transaction cost industry. Edison's design of tightly coupled generation, wires, and metering combined the entire vertical supply chain into a single firm, and given the available technologies, unbundling those transactions into separate market transactions required an ability to define and maintain property rights that did not exist. The vertically integrated structure of electric utilities is in large part a function of high transaction costs.

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28 This section draws on a more extensive discussion in Kiesling, "Implications of Smart Grid Innovation for Organizational Models in Electricity Distribution," in *Wiley Smart Grid Handbook*.

29 The economist Douglas Allen defines transaction costs as the costs of establishing and maintaining property rights, which are essential foundations of voluntary market exchange; see Douglas W. Allen, "What Are Transaction Costs?" *Research in Law and Economics* 14 (1991): 1–18, https://ssrn.com/abstract=3882114.

30 Ronald H. Coase, "The Nature of the Firm," *Economica 4*, no. 16 (1937): 386–405. This article was one of the works the Nobel committee cited in awarding Coase the Nobel Prize in economics in 1991. For more on Coase's influential work and its relevance to regulation and public policy, see Lynne Kiesling, *The Essential Ronald Coase* (Essential Scholar Series, Fraser Institute, 2021), https://www.essentialscholars.org/coase.

The transactional boundary of the firm, the delimiter of which transactions are more efficiently accomplished in markets, changes when technologies change transaction costs. When digital technologies reduce transaction costs, it is efficient for more transactions to shift toward markets and away from vertically integrated firms. The case studies in the next section provide some illustrations of the kinds of organizational and market changes that digitalization makes possible by reducing transaction costs.

An analogy to the telecommunications industry provides some insights. New mobile telephony technologies reduced transaction costs, which reduced the economic justification for vertically integrated telephone utilities and unleashed the digital creativity of the past two decades. In electricity, the invention of the combined-cycle gas turbine in the 1980s reduced the economies of scale in generation and made competitive wholesale markets feasible. This new technology, along with institutional changes in the form of Public Utility Regulatory Policies Act (PURPA) and the Energy Policy Act of 1992, combined to reduce transaction costs and reduce the economic justification for continuing the vertical integration of generation.[31]

Digitalization is now reducing transaction costs in most retail markets in the economy, and it can do so in electricity as well. Digital networks, digital platforms, and automation reduce the costs of transaction to exchange energy, and even to have DER owners participate in markets for grid services. It also opens up the economic feasibility of new organizational structures like microgrids around the edge of the distribution grid.

One organizational and operational implication of growing digitalization is the refinement of the utility business model into the Distribution System Operator (DSO). No national (or international) single model of a DSO exists, but the general definition of a DSO is an entity responsible for distributing and managing energy. What distinguishes the DSO model from the traditional distribution utility is the new and changing capabilities introduced by digital technologies and the new operational management challenges introduced by DER and digital innovations around the distribution edge. Taft, Kristov, and De Martini characterize this DSO transition

Another economic argument for less vertical integration and for unbundling generation and retail is grounded in competition policy, particularly the precedent established in the U.S. Department of Justice (US DOJ) settlement with AT&T in 1983 that led to the unbundling of the Bell System. AT&T owned the handset/customer premise equipment (CPE) manufacturer Western Electric as part of its vertically integrated, regulated monopoly. Western Electric was one of several CPE manufacturers in what could become a competitive downstream market. AT&T only purchased CPE from its affiliate, Western Electric. As part of the antitrust lawsuit, US DOJ argued that AT&T used its regulated monopoly position to exert anti-competitive influence in the downstream CPE market, and that requiring AT&T to unbundle Western Electric would reduce entry barriers and enable the CPE market to be more competitive, to the benefit of both consumers and competing CPE suppliers. This analysis was part of the US DOJ argument to "quarantine the monopoly" to match the regulated utility footprint to the portion of the vertical supply chain that has the natural monopoly characteristics that justify economic regulation.

The implication of the "Bell Doctrine" for a digitalized electric system is a reexamination of the economic justification for unbundling, given the transaction cost reducing effects of digital technologies, particularly consumer-facing digital technologies around the edge of the distribution grid. These technologies enable microgrids, automated market participation, and other ways to organize production and create economic and environmental value for consumers through innovation.[32]

31 The Public Utility Regulatory Policy Act of 1978 (PURPA, P.L., 95–617) was intended to reduce the monopoly power of regulated utilities and increase investment in renewable energy technologies by requiring utilities to buy electricity from third-party "qualifying facility" generators.

32 For more information and an application of this analysis to incumbent default service in restructured states, see Lynne Kiesling, "Incumbent Vertical Market Power, Experimentation, and Institutional Design in the Deregulating Electricity Industry," *Independent Review 19*, no. 2 (2014): 239–264.

as an evolution away from traditional one-way power flow and architecture to "N-way broad-access networks where any qualified entity can use the distribution network to carry out energy transactions with any other qualified connected entity and where buildings may become integral participants in real-time operations via pooling customer resources in order to seek access to different value streams."[33] Other DSO models exist, and the common traits they share emphasize using digital technologies to coordinate and manage an increasingly diverse and multidirectional electric power network.

At a more practical level, digitalization is prompting a reconsideration of the expenses on which utilities receive cost recovery and earn a regulated rate of return. The composition of the rate base will evolve beyond "iron in the ground" to include more IT assets, and expenses like IT/OT systems integration and cloud computing will straddle the asset/expenditure categories that usually delineates the composition of the rate base.[34]

This evolution presents some challenges for regulation. One challenge is the fundamentally different nature of these technologies, particularly their shorter life spans and the different accounting treatment of depreciation. These differences may also require a reevaluation of the "used and useful" rule because digital technologies are often replaced while still technically useful but nonetheless obsolete because of rapid innovation. A related challenge is regulator information asymmetry. New and heterogeneous digital technology expenses can be difficult for regulators to evaluate for prudency. Regulators and researchers should consider alternative regulation methods and ways to reduce the incentive misalignment arising from such information asymmetry about new technologies.

33 Jeffrey Taft, Lorenzo Kristov, and Paul De Martini, *A Reference Model for Distribution Grid Control in the 21st Century* (No. PNNL-24463, Pacific Northwest National Laboratory, July 2015), https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-24463.pdf. Figure 2, page 3.2, provides a useful representation of the key parties, physical power flows, and data flows in a DSO control environment.

34 NARUC has several resources relevant to this issue, for example, the resources and activities in the Center for Partnerships and Innovation's Electricity System Transition: Valuation and Ratemaking, available at https://www.naruc.org/cpi-1/electricity-system-transition/valuation-and-ratemaking/. In their Regulator's Financial Toolbox webinar series, see also their September 24, 2020, webinar on cloud computing, brief available at https://pubs.naruc.org/pub/0923A1BA-155D-0A36-3125-703210763F3C, and the March 2, 2021, webinar on advanced metering infrastructure, brief available at https://pubs.naruc.org/pub/4DE49EE6-1866-DAAC-99FB-B36D6E27919D.

IV. Illustrative Examples

Innovation and experimentation with new digital value propositions has been occurring incrementally over the past two decades. Here we highlight some illustrative examples of the new value propositions digitalization creates through automation, interoperability, modularity, and open-source design.

Automation

Customer and end-use automation is a capability that highlights the economic and environmental impacts of digitalization. Digital automation reduces the transaction costs and the time frames associated with taking actions, including both demand response and supply response, and when coupled with decentralized digital monitoring of system conditions, automation enables faster, targeted response to rapidly changing grid conditions. When coupled with machine learning and predictive analytics, automation can even enable actions in anticipation of grid conditions. For these reasons automation is an essential element of enhancing grid flexibility.[35]

Automation Example: Recurve

Recurve is an energy data management company focused on using data and automated price and event response to increase energy efficiency and reduce environmental impact. Their work integrates data on customer energy consumption, weather data, and building characteristics; puts those data in a uniform format; and uses those data (now made revenue-grade and standardized) in conjunction with power market operations in California to enable demand flexibility and adaptability to changes in system and market conditions. Recurve calls its system a demand flexibility management platform, and it uses automation and cloud computing to achieve this flexibility, coordinating the actions of its customers with market operations and system operations.

Recurve's customers include utilities, market operators, municipal utilities, and aggregators.[36] The California Public Utilities Commission and the California Independent System Operator (CAISO) reviewed and approved Recurve's model through docketed processes.

Recurve's platform relies on several of the core digitalization elements, particularly automation and open-source software. Automation enables Recurve's customers to see real-time or near-real-time consumption data that were invisible to them pre-digitalization. Seeing timely data allows those customers to take actions that enhance demand flexibility, to avoid costs and/or to coordinate with availability of low-carbon resources. It also enhances measurement and accounting transparency, particularly for difficult-to-observe variables like avoided CO_2 emissions that require real-time matching of multiple different variables and data sources.

Recurve's demand flexibility management platform is built on open-source software, as described above. Recurve has contributed two important projects to LF Energy for general open-source use: CalTRACK and OpenEEMeter.

CalTRACK is an open-source model for estimating energy savings and avoided energy use.[37] CalTRACK standardizes the measurement of avoided energy use, which is a diverse category of end-user actions and has thus been difficult to observe, measure, and take advantage of for flexibility purposes. The underlying model uses data on building characteristics and weather data to estimate a counterfactual: the building's energy use if the customer had not responded to a program call or a price signal. If the measured energy use of the building in response to a price signal or a demand response call is less than the counterfactual, that difference is recorded as measured energy savings, for which the building owner can be compensated

35 NREL researchers are working on designs for autonomous energy grids (AEGs) that use automation, artificial intelligence, and DER. For a description, see Benjamin Kroposki, Andrey Bernstein, Jennifer King, and Fei Ding, "Tomorrow's Power Grid Will Be Autonomous," *IEEE Spectrum* (November 2020), https://spectrum.ieee.org/tomorrows-power-grid-will-be-autonomous.

36 Recurve highlights some customer examples at https://www.recurve.com/customers.

37 https://www.CalTRACK.org.

according to the market design or utility program. OpenEEMeter is an open-source set of tools for calculating normalized metered energy consumption (NMEC). It includes the CalTRACK code for standardized estimates of normalized metered energy savings, and thus provides a useful framework for implementing demand response and end-user compensation based on measured energy savings.

Recurve's DemandFLEXMarket platform enables utilities to access, aggregate, and compensate demand flexibility. They can send a clear and transparent price signal that indicates their willingness to pay for demand flexibility to participants, based on the utility's estimate of the opportunity cost of grid conditions and the value of demand flexibility in alleviating a stress episode.[38] The DemandFLEXMarket platform uses both the CalTRACK and OpenEEMeter open-source resources.

Virtual Power Plant

Digitalization creates the potential to operate the grid differently and more efficiently than the previous combination of mechanical technologies and a centralized SCADA system. As discussed above, decentralized digitized grid operation harnesses interconnected, distributed sensors and resources to enhance grid reliability, flexibility, and resilience.[39]

Distribution automation enables real-time fault detection and repair; automation around the distribution edge enables DER to be flexible and to provide timely grid services. The integration of IT and OT into a single platform (IT/OT) is one of the primary factors enabling both system flexibility and decarbonization by making aggregation of DER feasible.

Organizing these distributed capabilities can take the form of virtualization.[40] Virtualization uses an IT network to represent the physical distribution network, and to enable digital sensors and controls to implement remote and automated (where appropriate) control and coordination in the distribution grid. Virtualization also takes advantage of data analytics and machine learning tools to analyze, estimate, and implement physical actions.

Combining virtualization with digital DER aggregation creates virtual power plants (VPPs). A VPP connects distributed, digitally grid-interactive resources into a resource network that can be managed to provide energy to a market or to provide grid services through flexible response to price signals or program calls.[41] To the extent that these resources are low carbon and the VPP substitutes for fossil fuel resources (particularly in peak periods when generation is both expensive and carbon-intensive), a VPP is a business model than can pay the end user for actions taken while also generating a profit for the aggregator and reducing emissions. VPPs are also easy to scale up and down depending on the number, type, and location of the interconnected resources; they illustrate the combination of interoperability and modularity that can reduce the cost and inconvenience of creating such a decentralized networked resource.

A VPP combines flexibility and dispatchability with distributed grid operations to optimize coordination of supply and demand in ways that are mutually beneficial to producers and consumers while also maintaining grid reliability. These capabilities mean that VPPs can enhance grid resilience while also contributing to decarbonization by dispatching low carbon resources and providing compensation that creates investment incentives.

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38 Jeff St. John, "Can a New Way to Pay for Behind-the-Meter Flexibility Help Prevent Rolling Blackouts in California?" Canary Media, April 19, 2021, https://www.canarymedia.com/articles/grid-edge/can-a-new-approach-to-demand-flexibility-help-save-california-from-rolling-blackouts.

39 For a collection of academic research on VPPs, see https://www.sciencedirect.com/topics/engineering/virtual-power-plant.

40 Astrid Atkinson, Varun Sivaram, and Richard L. Kauffman, "How to Unlock the Potential of Virtual Power Plants? Virtualize the Grid." Utility Dive, March 11, 2021, https://www.utilitydive.com/news/how-to-unlock-the-potential-of-virtual-power-plants-virtualize-the-grid/596497/.

41 Gene Wolf, "Virtual Power Plants: Some Assembly Required," T&D World, January 21, 2022, https://www.tdworld.com/distributed-energy-resources/article/21212528/virtual-power-plants-some-assembly-required.

As a design, the VPP can be implemented in diverse ways. Sonnen, for example, has VPP software to connect Sonnen batteries into a VPP, which they have built into a residential apartment neighborhood called Soleil Lofts south of Salt Lake City, Utah.[42] Tesla offers an opt-in VPP for Powerwall owners in California to provide grid services, albeit without direct compensation.[43] While not fully realizing the interoperability and market benefits of interconnecting diverse devices and compensating device operator actions, these proprietary systems have some features of VPPs that enable them to provide grid services.

VPP Example: Site Controls

An early prototype of the VPP design was Site Controls, an energy management system service provider for commercial customers with multiple locations (e.g., retail store or restaurant chains). Site Controls provided its customers with an energy management system and local area network connecting its various locations, and this system enabled customers to reduce their energy expenses and reduce system demand volatility without discomfort or inconvenience to them or their customers. Networking buildings in various locations together also allowed customers to arbitrage differences in wholesale market prices across different markets, reducing consumption in expensive markets. By 2008 they managed over 220 MW of peak demand, with 130 MW of it dispatchable.[44] Site Controls also had multiple customers in San Diego, where they were able to activate considerable demand response during a 2007 wildfire. By 2010,

> In San Diego the company has aggregated 300 businesses and subscribed them to a dispatch load network. As a result, the company has the capacity reduce power loads so substantially that it essentially acts as a virtual generator in that market.[45]

Site Controls was later acquired by Siemens and now continues operations as Siemens Site Controls.[46]

VPP Example: OhmConnect

OhmConnect operates in California and aggregates residential customers into a VPP.[47] Their service offering is an overlay on top of the customer's existing utility relationship and tariff. Utilities, other load-serving entities, and wholesale market transactions pay OhmConnect for delivered demand reductions during times of high grid stress. In those periods, OhmConnect's demand flexibility offers an alternative to the traditional responses to congested periods: bring an expensive and carbon-intensive peaking power plant on-line, ask for voluntary reductions, or institute blackouts. OhmConnect delivers this flexibility by connecting their customers together on a digital platform and then using the revenue they make to pay individual customers to change their appliance and device settings.

Customers can respond to advance notifications to reduce their energy use for up to an hour (OhmHour) by receiving direct communications via email or text message. Notifications can also go directly to their home area network, smart plugs, or grid-interactive digital devices to provide an automated response. Customers with such automation capabilities can also be paid to change their settings automatically during an AutoOhm, which is a real-time flexibility request when the grid is under extreme stress. OhmConnect's service is currently compatible with over 20 different digital devices, including thermostats, smart plugs, and smart home systems. OhmConnect also offers its customers algorithms to use on the If This Then That (IFTTT) automation platform,

42 https://sonnenusa.com/en/virtual-power-plant/.

43 https://www.tesla.com/support/energy/powerwall/own/california-virtual-power-plant.

44 Ken Sinclair Interview with Dan Sharplin, "On-Demand Energy and Asset Management Solutions," Automatedbuildings.com, August 2008, https://automatedbuildings.com/news/aug08/interviews/080730031707sharplin.htm.

45 "Site Controls: Taking Control of Energy Usage," Austin Business Journal, June 13, 2010, https://www.bizjournals.com/austin/stories/2010/06/14/focus5.html.

46 https://assets.new.siemens.com/siemens/assets/api/uuid:6af81177-7c45-476b-9191-080cbf47ca8d/version:1560794373/bt-cc-site-controls-enterprise-portal-brochure-en.pdf

47 https://www.ohmconnect.com/.

making customer participation in demand flexibility easier and more convenient. Their platform is implicitly a bring-your-own-device (BYOD) platform, being device agnostic with standard interfaces.

OhmConnect was operating in California during the August 2020 heat-related outages. Recurve (described above) performed an analysis of CAISO market data to assess OhmConnect's performance in providing demand reductions during those high-stress periods. Recurve's analysis suggests that OhmConnect's customers reduced their demand by 19 percent, a considerable reduction.[48] Recurve's analysis also identifies aspects of California's regulatory institutions that create barriers to demand-side participation, particularly inconsistency in the definition and measurement of demand reduction across CAISO and various energy agencies.[49]

In December 2020 OhmConnect announced the construction of Resi-Station, a residential network-based VPP in California.[50] Their goal with Resi-Station is to connect hundreds of thousands of California homes to create the flexibility potential of 550 MW of power.

OhmConnect's business model embodies the architectural features of digitalization. They use network interconnection to create an integrated IT/OT platform, implement automation with their customers who have grid-interactive digital devices, exploit interoperability to focus on device capability and not restrict participation to a single manufacturer, and take advantage of modularity of these diverse digital devices to be able to scale their VPP goal up to an ambitious 550 MW in California.

Transactive Energy

Digitalization and IT/OT system integration has also enabled research and development in transactive energy systems. According to the GridWise Architecture Council, transactive energy refers to

> … techniques for managing the generation, consumption or flow of electric power within an electric power system through the use of economic or market-based constructs while considering grid reliability constraints. The term "transactive" comes from considering that decisions are made based on a value. These decisions may be analogous to or literally economic transactions.[51]

In a transactive energy system, market transactions empower buyers and sellers to make physical energy decisions based on their individual valuations of those decisions. From an engineering perspective, the market-clearing price becomes the system control signal, indicating to the participants how to change their behavior (or the behavior of their devices) in ways to provide decentralized coordination, in contrast to requiring only centralized control-room control over the distribution system. By deliberate architectural design, a transactive energy system is capable of interconnecting and coordinating different resources participating in the market: thermostats, water heaters, EV charging (and discharging to provide energy or grid services), behind-the-meter storage, and residential solar PV. Transactive systems differ from existing VPPs because in a transactive system, a market price is the engineering control signal, rather than the control signal arising from, say, an emergency call from the system operator. VPPs can be designed and operated as transactive systems.

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48 Marc Paré, Mariano Teehan, Stephen Suffian, Joe Glass, Adam Scheer, McGee Young, and Matt Golden, *Applying Energy Differential Privacy to Enable Measurement of the OhmConnect Virtual Power Plant: A Study of Demand Response during the California August 2020 Blackouts* (Recurve, prepared for the U.S. Department of Energy and the National Renewable Energy Laboratory, December 2020), 9, https://assets.website-files.com/5cb0a177570549b5f11b9550/5ffddb83b5ea5d67f5c43661_Quantifying%20The%20OhmConnect%20Virtual%20Power%20Plant%20During%20the%20California%20Blackouts.pdf.

49 Paré et al., *Applying Energy Differential Privacy to Enable Measurement*, 6.

50 https://www.ohmconnect.com/about-us/news/resi-station; see also Jean Haggerty, "World's Largest Residential Virtual Power Plant Coming from Alphabet-Backed SIP and OhmConnect," *PV Magazine*, December 7, 2020, https://pv-magazine-usa.com/2020/12/07/worlds-largest-residential-virtual-power-plant-coming-from-alphabet-backed-sip-and-ohmconnect/.

51 https://gridwiseac.org/index.php/intro-to-transactive-energy/.

Transactive Energy Example: GridWise Olympic Peninsula Project

Transactive energy systems emerged out of work at the Pacific Northwest National Laboratory in the 2000s focused on improving the economic and operational efficiency of distribution systems. In systems with fixed, regulated rates, peaking behavior is common, and peak generation resources are costly, have poor emission profiles, and have poor capacity utilization. This work explored using digital technologies, market design, and automation to make demand more responsive and flexible, enabling supply-demand coordination and customer satisfaction without the need for such costly peak resource investments.

The first transactive energy research project, the GridWise Olympic Peninsula Testbed Demonstration Project, was a field experiment that equipped 130 households in the Olympic Peninsula with a two-way programmable thermostat that could be programmed to respond autonomously to data it received. The households also had a website for viewing their energy consumption and billing. The experimental aspect of the project divided them into four groups. In addition to a control group that received the technology for viewing energy consumption, three treatment groups received different contractual arrangements for how they would be compensated for changing their behavior in response to price signals: a fixed price contract, a time of use plus critical peak pricing contract, and a real-time pricing contract. Each household received a quarterly payment with which to pay for their consumption, retaining any remaining balance at the end of the quarter.

At the end of the pilot, the households in the real-time transactive market saved close to 20 percent compared to their counterfactual fixed-rate utility bill, and their automated market participation contributed (along with the time of use customers) to reducing peak demand. Although this project occurred before the increase in DER investments, its results pointed to the potential for markets and automation to increase demand flexibility at little cost or inconvenience to end users.[52]

Transactive Energy Example: TeMix

TeMix is a standards-based financial market platform approach to transactive energy systems.[53] Using an open standard protocol for defining products, quantities, and other dimensions of transactions, the TeMix platform design uses tender offers, which are binding delivery offers of price and quantity. A transaction occurs when a counterparty accepts a tender offer. The TeMix platform offers three transactive energy markets: 5-minute, 15-minute, and hourly. This design is an example of "Type 1" transactive energy, the communication of supply-focused scarcity prices to customer devices and using automation at that device level to respond to those prices.

In 2016, Universal Devices and TeMix received a grant from the California Energy Commission (CEC) to apply the TeMix platform in constructing a Retail Automated Transactive Energy System (RATES) with Southern California Edison.[54] The RATES platform has two components: a retail dynamic pricing rate to which customers can opt in and a subscription structure that combines the dynamic rate with other pricing dimensions for fixed charges and protection against high price volatility. The dynamic rate is based on wholesale locational marginal prices (LMP) from the CAISO hourly, 15-minute, and 5-minute markets, and thus communicates locational scarcity information to retail customers. The TeMix platform includes interoperable standard protocols for communicating the pricing (tender/offer) information, and a set of software agents to gather information from a variety of devices (thermostats, pool pumps, batteries, EVs, and appliances) that use machine learning to model and predict the behavior of the devices. These agents also allow for automation of customer responses to the dynamic rate.

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52 D. Hammerstrom, R. Ambrosio, J. Brous, T. Carlon, D. Chassin, J. DeSteese, R. Guttromson, G. Horst, O. Järregren, R. Kajfasz, S. Katipamula, L. Kiesling, N. Le, P. Michie, T. Oliver, R. Pratt, S. Thompson, and M. Yao, "Pacific Northwest GridWise™ Testbed Demonstration Projects, Volume I: The Olympic Peninsula Project," (Technical Report to the U.S. Department of Energy, 2007); see also David Chassin and Lynne Kiesling, "Decentralized Coordination through Digital Technology, Dynamic Pricing, and Customer-Driven Control: The GridWise Testbed Demonstration Project," Electricity Journal 21 (2008): 51–59.

53 https://temix.com.

54 https://rates.energy/.

Approximately 115 residential customers participated in the RATES pilot, some of whom had behind-the-meter solar systems. Program participation gave them access to a digital thermostat and voice-activation devices as well as a home energy management device. The final report to the CEC indicates that the technologies performed as anticipated during the pilot project, and that the project allowed TeMix to improve their processes and algorithms. The report does not provide an assessment of overall individual bill savings or consumption changes as a result of participating in the RATES pilot.[55]

Transactive Energy Example: TESS

Transactive Energy Service System (TESS) is a research and implementation project led by SLAC National Laboratory's Grid Integration, Systems and Mobility group (GISMo). TESS is designed to employ all the features of digitalization: network interconnection for DER, automation of responses to prices, interoperability and modularity of system components and interfaces, and reliance on and development of open-source software as the basis for the platform.[56] These design features combine to create the potential for more flexibility and resilience.

In October 2019, the GISMo team began working with Holy Cross Energy (HCE), an electric cooperative in Colorado, to develop the TESS platform for managing its coincident peak charges from its wholesale supplier. HCE is a partner in the Basalt Vista project, a new affordable housing development in Basalt, Colorado, with rooftop solar PV, EV charging capabilities, and digital home energy management system connections for other devices.[57] These digital capabilities prepare these homes for participation in a transactive energy system like TESS.[58]

While earlier projects and the TeMix design focus on communicating prices to devices and enabling devices to respond autonomously, TESS goes one step further and employs a "Type 2" prices from devices design that incorporates the buyers' willingness to pay as well as the costs to sellers. The TESS design is built on a particular market design called a double auction, in which buyers submit bids and suppliers submit offers in each market period. The market maker gathers the bids into a demand curve and the offers into a supply curve, determines the market-clearing price in that market period, and communicates the results to the participants. All bids, offers, and responses to the market-clearing price that emerge can be automated through the TESS platform, reducing the transaction costs of market participation and making it easy for even residential customers to transact.

The TESS market design builds on the market design used in the GridWise Olympic Peninsula Project and enables devices to submit active, automated bids. Different types of devices have different bidding functions that reflect both their technology features and the individual preferences of the end users/device owners.

The TESS team (SLAC GISMo, Post Road Foundation, and Knowledge Problem LLC) have received a research grant from the U.S. Department of Energy for developing grid-interactive efficient buildings (GEBs). This TESS 2.0 project, in partnership with New Hampshire Electric Cooperative and Efficiency Maine, will develop the capabilities of a transactive energy system to "harmonize communications and optimize energy use among the distributed energy resources, local energy markets, and buildings of three rural communities."[59]

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55 Edward Cazalet, Michel Kohanim, and Orly Hasidim, Complete and Low-Cost Retail Automated Transactive Energy System (RATES) (CEC 500-2020-038, Report submitted to the California Energy Commission, June 2020). Appendix B provides information on the participants and the nature of their uses of the technologies and degree of active participation.

56 A description of the TESS project and the entire code base are available at https://github.com/slacgismo/TESS.

57 Another important project in progress at Basalt Vista is NREL's Network Optimized Distributed Energy Systems (NODES) pilot, which in combination with NREL's AEG work harness digitalization to enable flexibility and enhanced DER integration. For an overview, see https://www.nrel.gov/news/features/2019/small-colorado-utility-sets-national-renewable-electricity-example-using-nrel-algorithms.html.

58 Marie-Louise Arlt, David P. Chassin, and Lynne Kiesling, "Opening Up Transactive Systems: Introducing TESS and Specification in a Field Deployment," Energies 14, no. 13 (2021): 3970–3992, https://doi.org/10.3390/en14133970.

59 https://www.energy.gov/articles/doe-invests-61-million-smart-buildings-accelerate-renewable-energy-adoption-and-grid.

Transactive Energy: DSO + T

In 2022 the Pacific Northwest National Laboratory published a report on their four-year analysis of a DSO with a transactive system.[60] Focusing on estimating the potential demand flexibility in such a system, the DSO+T study was an integrated simulation of distribution grid operations and extensive digital sensing, monitoring, and automation capabilities among participants around the grid edge. The study's purpose was defined as follows.

> There is a need for a solution that integrates the coordination of demand flexibility into everyday grid operation, ensures it is automated, puts the customer in control of how much or little they participate, and fairly compensates them for the level of flexibility they provide to the grid. What would such a system look like when deployed at scale? Would it achieve effective and stable coordination of a large number and range of end-loads? How much could peak load be reduced to ensure reliable electric service? And what is the impact on the customer's pocketbook?[61]

The study assessed both the engineering and economic feasibility and impact of a DSO using a transactive system. In addition to a business-as-usual case, they examined both moderate and high DER cases and estimated the economic value flows through the system in each case to all distribution system participants. Using data from Electric Reliability Council of Texas (ERCOT) and simulating 100 generators and 60,000 customer buildings, the analysis suggests that transactive coordination could reduce peak demand by between 9 and 15 percent and reduce demand volatility by between 20 and 44 percent, depending on scenario. The estimated aggregate economic benefit was between $3.3 and $5 billion, due to lower electricity prices, better coordination, and the reduced need for investment due to improved capacity utilization.

Substation Automation and Virtualization

Substations are essential components of the distribution system. With switches, circuits, and devices for control and protection of the distribution grid, substations contribute to grid reliability. In the electro-mechanical grid of the 20th century, control room operators did not have much visibility into the real-time operations within substations, so their control and protection capabilities were limited.

Digital technologies change what substations can accomplish and how much information they can provide to grid operators. Sensing, monitoring, and automation capabilities within substations can identify problems and even prevent outages that previously would have been unavoidable, increasing reliability and reducing load losses. These capabilities also increase grid resilience by automating actions required for a return to normal operations. Substations can not only be automated, they can also be virtualized, which means they can be operated remotely using a virtual computing environment. Virtualization abstracts the operation of the system from the actual hardware of the system, as discussed earlier in the context of creating VPPs. Virtualization can contribute substantially to resilience and is used in a wide range of industries to reduce system downtime and to enable faster disaster recovery.

In 2020 LF Energy introduced an initiative to build a catalog of open-source software for substation automation and virtualization. Their Digital Substation Automation Systems (DSAS) initiative invited collaboration to create software modules for substation systems that are interoperable and can be scaled up or down to suit different substation configurations. One important capability that substation automation (and, eventually, virtualization) will deliver is faster and more adaptable operations with higher DER penetration; such automation will better enable substations to handle fluctuating supply from renewables and demand from EVs. The first project in the DSAS initiative is CoMPAS—Configuration Modules for Power Industry Automation Systems.[62] CoMPAS is a project to build software components for substation automation that meet the IEC 61850 industry standard (as discussed in Section 3).

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60 https://www.pnnl.gov/projects/transactive-systems-program/dsot-study.

61 Pacific Northwest National Laboratory, *The Distribution System Operator with Transactive (DSO+T) Study Executive Summary* (PNNL-32170-Sum, January 2022), 3, https://www.pnnl.gov/sites/default/files/media/file/EED_1574_BROCH_DSOT-ExecSumm_v11.pdf.

62 https://www.lfenergy.org/projects/compas/.

V. Conclusions and Action Steps for Commissions

The combination of digitalization and DER innovations has considerable implications for utility regulators. Many states are experiencing substantial DER investment and the forecast growth of EVs, as well as new renewables coming on to the bulk power system. These evolutions will create both opportunities and challenges for PUCs that oversee distribution (and in some states, transmission) system planning and perform traditional economic regulation functions while also mapping out clean energy transition pathways and implementing state clean energy requirements.

The role of PUCs is to attempt to align utility investment plans with a definition of the broader public interest. To the extent that cost-effective decarbonization is in the public interest, digitalization is a primary enabler of decarbonization by facilitating DER interconnection, visible and beneficial operations, and market transactions. Embracing digitalization, changes to grid architecture, and new approaches and business models can make the transition more streamlined and more efficient with fewer transaction costs, and lower costs. Understanding what these changes imply for grid architecture at a conceptual level, as discussed in this report, is essential for decision making about utility investments to enable cost-effective transition.

A large implication of digitalization and DER innovations is not just changing grid architecture, but also changing organizational architecture. Digitalization has powerful decentralizing forces that enable more decentralized coordination, and the achievement of important objectives like reliability in a more decentralized way, harnessing automation to enhance flexibility. Nonutility parties, from customers themselves to third-party service providers, can offer value-enhancing services to each other, and to the utility/DSO, through grid and organizational architectures that allow an interactive grid model. Not allowing broad participation may mean not taking full advantage of the benefits that these technologies offer, and that lost opportunity could mean higher costs for more redundant infrastructure.

This report has highlighted the benefits of digitalization: increased grid reliability, stability, and resilience; better-informed operational decision making; increased customer control and choice; and greater economic and environmental benefits arising from more extensive DER interconnection and use. Ideally, the economic benefits will accrue to both direct participants (e.g., a customer with automated response to dynamic rates) and the total system, and therefore all rate payers. Nevertheless, these benefits will not be realized without economic investments and attention to policies and processes that reduce impediments to their deployment.

In addition to the financial costs of digitalization investments, digitalization in electricity faces challenges. Technology researcher Karen Marcus highlights the following:[63]

- Lack of employees with data and domain expertise,
- Lack of strategic planning,
- Lack of overarching digital transformation scheme,
- Inability to address security issues,
- Inability to shift to a new business model,
- Inability to modernize the customer experience and strengthen the partnership between utilities and customers,
- Shareholder resistance if utilities are perceived to be earning lower revenues as a result of increased efficiency, and
- Customer resistance, especially if new technology is perceived to be faulty or dangerous or to increase costs.

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63 Karen Marcus, "Benefits and Challenges of Grid Digitization in 2021," Energy Central, January 12, 2021, https://energycentral.com/c/gr/benefits-and-challenges-grid-digitization-2021.

One aspect of strategic planning that she did not highlight is planning for big data. DSOs will generate substantial amounts of data with digitalization, and planning for its ownership rights, third-party and customer use rights, storage and access, and privacy is essential.

Actions Commissions Can Take

To realize the benefits and overcome the challenges of digitalization, commissions can take steps to enable its cost-effective implementation. Each state's situation varies, but some concrete approaches that can apply in a rate case, integrated resource planning (IRP), grid modernization, advanced metering infrastructure (AMI) upgrade, or transportation electrification proceeding are listed below. In all cases, commissions should acknowledge the potential risk of exacerbating existing economic and societal inequities.

- **Cultivate awareness and education:** Encourage commissioners, staff members, and utilities to stay up-to-date on digitalization-related topics, such as interconnection standards, interoperability, and cybersecurity. NARUC and other organizations provide resources on these topics. Commissions that take advantage of these resources will be better positioned to guide decision making in directions that can overcome the reticence to change.
- **Build an information access and data governance framework:** Utilities and users of the electric system will co-create both customer and system data. A shared data taxonomy and a framework for how data can be used by different parties will enable the benefits of digitalization.[64] Having an explicit data governance framework that enables customers and third parties to access those customer and system data while respecting privacy is an important building block for a forward-looking, cost-effective, participatory approach to utility investments for clean energy transitions. Some examples include the United Kingdom's Data Sharing Governance Framework (https://www.gov.uk/government/publications/data-sharing-governance-framework/data-sharing-governance-framework) and New York State's GIS Data Sharing Cooperative (https://gis.ny.gov/co-op/).
- **Ask utilities to provide systematic analyses of digitalization benefits and costs:**

  For example:
  - Encourage strategic planning by asking utilities for their grid digitalization investment plans.
  - If a utility proposes grid modernization investments, require the use of industry standards such as IEC, IEEE, NIST, and/or other open standards to enable interoperability and standard device interconnection.
  - If a utility proposes grid modernization investments, ask them to provide a strategic data management plan.
  - If a utility includes operations and maintenance requests in a rate case, ask them why they did or did not incorporate digital approaches such as software as a service (SaaS), cloud computing, or open-source architecture and software.
  - In a transportation electrification proceeding, ask about planned use of industry standards and interoperability, and whether they can provide an analysis of a platform using open-source software.
- **Review existing regulations:** Some of digitalization's benefits arise from new grid architectures and new participatory business models and models of community engagement. Existing regulations may prevent such potentially beneficial arrangements from emerging. For example, if regulations prevent local microgrids that could be a useful resource during peak or emergency conditions, that regulation is no longer a good fit with the technologies and potential value propositions that now exist. In some

64 A shared data taxonomy also overlaps with interoperability, which requires that all parties have a shared definition and understanding of the meaning of data.

cases, these maladaptive existing regulations also have negative equity implications, another reason to reconsider them.

- **Experiment:** Consider adopting accelerated pilot approval processes (e.g., regulatory "sandboxes") and other venues for experimentation with new grid architecture models and organizational models. For large, systemic changes like digitalization, the immense nature of the change can frequently be a hurdle, and the complexity can be used to stifle participation from nonutility participants like customers and third parties. Small-scale experimentation is a process for learning more about the benefits and costs of technological or business model changes while breaking down some of the barriers.

NARUC has created resources over the past few years that offer additional information and insights on specific topics and next steps related to this primer. Readers might be interested in:

- **Webinar: August 10, 2021, Regulator's Financial Toolbox: Communications Networks**
  The Regulator's Financial Toolbox series is where technology meets bookkeeping. On the Communications Networks webinar, utility regulators hear multiple perspectives about how communications networks work, what is unique about distribution system and grid edge communications vis-à-vis the distribution system and bulk power system communications, what benefits communications networks provide to the electricity system, and considerations specifically for regulators. Like many things, the right communications solution will be up to the jurisdiction, but this webinar provides a framework for making decisions to help regulators be prepared to engage with utilities on this thorny issue.

  View speaker biographies and presentations
  View recording
  View summary

- **Webinar: March 2, 2021, Regulator's Financial Toolbox: Advanced Metering Infrastructure**
  The Regulator's Financial Toolbox Series examines regulatory issues where technology meets bookkeeping. In this 90-minute webinar, speakers addressed technology, uses, costs and benefits, and future opportunities for advanced metering infrastructure (AMI). This webinar explains what AMI is and does, examples of benefits of AMI, AMI's role in enabling a more resilient system, regulatory considerations for AMI, and the future for AMI.

  View recording
  View brief
  View presentation

- **Webinar: September 24, 2020, Regulator's Financial Toolbox: Cloud Computing**
  The Regulator's Financial Toolbox series examines regulatory issues where technology meets bookkeeping. In this 90-minute webinar, speakers address technology, economic, and accounting considerations for cloud computing. This webinar explains what cloud computing is (and is not) and addresses regulatory considerations for the utility leveraging cloud computing.

  View recording
  View brief
  View presentation

- **Smart Grid Interoperability: Prompts for State Regulators to Engage Utilities (April 21, 2020)**
  As technologies proliferate across the electricity network, interoperability is increasing in importance to enable communication, coordination, and integration of more components essential to the network—some of which may not be owned by the utility. Interoperability is a means to ensure that operational network components work collaboratively and efficiently with each other. Investments that emphasize interoperability can improve reliability and security, reduce design and installation costs, and enable new

services by preserving competitive innovation. This paper outlines roles, responsibilities, and actions that a state regulator may consider in its review of utility proposals for investments in smart grid technologies to ensure these investments align with good interoperability practice.

- **Understanding Cybersecurity for the Smart Grid: Questions for Utilities (December 2020)**
  This paper explores cybersecurity topics associated with the continued technology-driven evolution of the electric grid. It includes questions that PUCs might ask utilities to better understand how they are assessing and mitigating challenging new risks. Concepts in this paper draw from seminal works by the NIST; it is a complement to Understanding Cybersecurity Preparedness: Questions for Utilities, a component of NARUC's Cybersecurity Manual.

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