Connecting Threads to Create a Roadmap to an Intelligent Energy Future

Paul Centolella, Chair NIST Smart Grid Advisory Committee

This memo encourages the National Institute of Standards and Technology, working with the U.S. Department Energy and other stakeholders, to consider the impacts of significant power system challenges and technological changes and how to bring together different research threads to develop a forward-looking response. It summarizes a topic that the Advisory Committee may wish to consider in a future meeting.

Background: The Challenges

Converging forces will fundamentally change the power system over the next five to ten years.

The power system itself faces simultaneous challenges to:

- Remain affordable;
- Maintain reliability for an economy that has grown increasingly dependent on electricity;
- Become resilient with respect to severe weather impacts and to other disruptive events;
- Defend, deter, and recover from continuously evolving cyber-physical security threats; and
- Transition to an environmentally sustainable, low greenhouse gas energy system that integrates variable renewable resources and supports the electrification of transportation and other energy uses.

Individually any of these would be significant challenges. However, the industry must simultaneously remain affordable, improve reliability, and meet higher resilience, security, or environmental requirements.

Public concern related to resilience and climate change mitigation have produced policy responses and increased adoption of distributed and renewable energy resources and electric vehicles. As a result:

- The combination of declining technology costs, reliability and environmental concerns, and state policies are expected to support continued growth in the deployment of distributed energy resources.[1] Annual capacity additions of distributed generation and storage could increase by 70% by 2024.[2] As much as 50 GW of new distributed generating capacity could be added by 2030.[3]

---

[1] Federal Energy Regulatory Commission Staff. 2018. *Distributed Energy Resources: Technical Considerations for the Bulk Power System.* FERC Docket No. AD18-10-000.

[2] Vrins, J. 2016. *Take Control of Your Future, Part II: The Power of Customer Choice and Changing Demands.* Navigant Research. Available at: https://www.navigantresearch.com/news-and-views/take-control-of-your-future-part-ii-the-power-of-customer-choice-and-changing-demands.

[3] EIA. 2019. *Annual Energy Outlook 2019.* Available at: https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf.

- Over 15 GW of new wind and solar generation are expected to come on line in 2019, representing 64% of all new generating capacity.[4] This growth reflects, in part, a 69% decline in the unsubsidized levelized cost of wind and an 88% reduction in the unsubsidized levelized cost of utility-scale solar from 2009 to 2018, helping to make the addition of wind and solar generation competitive with the marginal operating costs of existing coal-fired power plants.[5] Given lower costs and the availability of tax credits, the United States is projected to add a total of 72 GW of wind and solar between 2018 and 2021. While the pace of investment in renewables may slow at least temporarily when tax credits expire, wind and solar will continue to represent a significant and rapidly growing portion of U.S. electric generation.[6]
- U.S. sales of electric vehicles (EVs) increased by 80% from 2017 to 2018.[7] Automakers are expected to be producing more than 280 different EV models by 2022.[8] And, EVs could account for as much as 40% of U.S. new car sales by 2030.[9]

System operators, utilities, and regulators are grappling with how to integrate the consumer and policy driven adoption of these technologies into the power grid.

Integrating distributed and renewable resources and electric vehicles, while becoming more reliable, resilient and secure creates significant challenges, including, for example, the need in some cases to:

- Manage gigawatt scale ramps to offset changes in the output of solar and wind resources that shift hourly, seasonally, and with local weather conditions;[10]
- Buffer rapid, often sub-interval changes in the output of distributed and renewable resources;
- Avoid distribution constraints created by local peaks that shift over time and do not coincide with system peak demand;[11]
- Sequence the charging of EVs to avoid overloading transformers and distribution lines,[12]

---

[4] EIA. 2019. *New electric generating capacity in 2019 will come from renewables and natural gas.* Available at: https://www.eia.gov/todayinenergy/detail.php?id=37952.

[5] Lazard. 2018. *Lazard's Levelized Cost of Energy Analysis, Version 12.0.*

[6] EIA. 2019. *Annual Energy Outlook 2019.* Available at: https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf.

[7] Inside EVs. 2019. *Monthly Plug-in EV Sales Scorecard.* Available at: https://insideevs.com/monthly-plug-in-sales-scorecard/. Downloaded January 15, 2019.

[8] Bloomberg New Energy Finance. 2018. *Electric Vehicle Outlook 2018.* See: https://bnef.turtl.co/story/evo2018?teaser=true.

[9] Bloomberg New Energy Finance. 2017. *Electric Vehicle Outlook 2017.*

[10] S. Meyn. 2017. "Distributed Control Design for Balancing the Grid Using Flexible Loads," National Renewable Energy Laboratory Autonomous Energy Grids Workshop. September 13-14, 2017.

[11] For example, in Consolidated Edison's New York service territory only 22% of distribution network peaks coincide with the system peak and, as of 2016, 50% of incremental PV installations were being deployed in night peaking networks. S. Mahnovski and S. Wemple. 2016. *The Role of Distributed Energy Resources in New York State.* Presentation to the U.S. Department of Energy Electricity Advisory Committee, Smart Grid Subcommittee.

[12] Simultaneous Level 2 charging of clusters of EVs could impact local transformers and distribution circuits. A majority of commercial charging stations and a subset of home charging in the U.S. are Level 2 chargers drawing 220V and representing approximately 7.2kW of demand per station. The demand from pair of these stations could start to approach that of small home. A DC Fast Charger represents a potential 50 kW demand and a Tesla Super Charger 140 kW. A Dutch charge point provider, Fastned, was the first to deploy an Extreme Fast Charger with a

- Create a reliable and resilient system that remains stable as circuits are reconfigured and parts of the network may be islanded to maintain critical services during a disruptive event;
- Maintain the cyber-physical security of the power system plus the gas pipelines, fuel transport, communications and other interdependent systems on which the electric grid relies; and
- Maintain the security of a power system which is, in part, inherently open, providing power to billions of internet connected devices.

Coincident with the challenges facing the power system, technological innovation is transforming the larger economy. The Internet of Things and Machine Learning are creating devices, buildings, vehicles, and resources that have "distributed intelligence." Inexpensive embedded processors and sensors, ubiquitous connectivity, advances in data analytics and machine learning are enabling devices and systems to autonomously optimize their performance.[13] While the exact time frames may vary, significant segments of electricity demand and most distributed resources are likely to have such intelligent capabilities within the next five to ten years. For example:

- With lower prices, currently below $100 for some well-known brands, the adoption of smart thermostats is accelerating. As of 2017, approximately 14 million or 13% of U.S. households had smart thermostats.[14] As many as 30% of U.S. homes are expected to have smart thermostats by 2020.[15] By 2023, the adoption of smart thermostats in the U.S. could create more than 40 GW of residential flexible demand.[16] These devices can shift demand out of high cost hours by pre-cooling homes and, in some cases, reducing peak air conditioning demand by 50% of more.[17] Smart thermostats and other

---

350 kW demand. Other vendors are expected to follow their lead. T. Bohn. 2017. "Electric Vehicle and Infrastructure Issues: Current & Future EV Charging Technology, Potential Impact on Distribution System," Wisconsin Public Utility Institute Workshop on Powering a More Electric Economy. October 26, 2017; S. Ravens. 2018. *Charging Ahead with EV Analytics: Adopting a Flexible Approach to IoT Infrastructure for EV Integration.* London, U.K.: Navigant Research.

[13] M. Porter and J. Heppelmann. 2014. "How Smart, Connected Products are Transforming Competition," *Harvard Business Review.* November 2014.

[14] Liu, J, 2018. *Ownership of Smart Thermostats Reaches 13% in the U.S.* SMAHome. See: https://mysmahome.com/news/42710/ownership-smart-thermostat-reaches-13-u-s/

[15] Stubbe, R. 2018. "Consumers Getting Hot for Smart Thermostats," *Bloomberg Business Week.* See: https://www.bloomberg.com/news/articles/2018-01-02/consumers-getting-hot-for-smart-thermostats; Parks Associates. 2017. https://www.prnewswire.com/news-releases/parks-associates-more-than-100-million-us-households-do-not-have-a-smart-home-device-300450441.html.

[16] Wang, F. 2018. *Residential Flexibility Potential in the U.S.* New York, N.Y.: Wood MacKenzie.

[17] J. Robinson, R. Narayanamurthy, B. Clarin, C. Lee and P. Bansal. 2016. "National Study of Potential of Smart thermostats for Energy Efficiency and Demand Response," *Proceedings of the 2016 ACEEE Summer Study on Energy Efficiency in Buildings.* Washington, D.C.: American Council for an Energy Efficient Economy; M. Harding and C. Lamarche. 2016. "Empowering Consumers Through Data and Smart Technology: Experimental Evidence on the Consequences of Time-of-Use Electricity Pricing Policies," *Journal of Policy Analysis and Management.* Vo. 35, No. 4; K. Herter & Y. Okuneva. 2014. *SMUD's Smart Thermostat Pilot – Load Impact Evaluation.* Sacramento, CA: Sacramento Municipal Utility District; Nest. 2014. *Our First Rush Hour Rewards results.* Available at: https://nest.com/blog/2013/07/18/our-first-rush-hour-rewards-results/; Application of Nevada Power

intelligent devices, smart refrigerators and water heaters, can control the kind of minor temperature variations that otherwise occur randomly to shift the timing of a large portion of residential demand without compromising service.[18]

- In commercial buildings, the potential to reduce costs and improve worker performance is increasing the integration of sensors into building management systems and the applications of smart building technology.[19] Taking advantage of thermal inertia, a simple pre-cooling strategy could reduce peak demand in commercial buildings by an estimated 16%.[20] With intelligent sensing and control, a more sophisticated optimization which considers weather and occupancy forecasts and forward electricity prices, could provide as much as 50% demand and energy savings in commercial buildings without sacrificing indoor air quality or occupant comfort.[21] Flexible industrial process and pumping loads also are significant and increasingly will be optimized on continuous basis.[22]
- While EVs will increase total electricity usage, smart charging has the potential create flexible demand and support the integration of additional renewable resources.[23]
- Intelligent control technology is already being applied help optimize the operation of distributed generation and storage.[24]
- The power grid itself is becoming more automated as emerging technologies provide for automatic fault isolation, microgrid control, Volt-VAr optimization, and power flow control and more dynamic with enhanced real-time visibility, dynamic line and equipment ratings, and topology control. To achieve increased resilience, the grid may well evolve toward an autonomous, fractal system in which cell-like blocks can self-

---

Company d/b/a NV Energy for Approval of its 2014 Annual Demand Side Management Update Report as it relates to the Action Plan of its 2013-2032 Triennial Integrated Resource Plan, Volume 5 – Technical Appendix, available at: http://pucweb1.state.nv.us/PUC2/DktDetail.aspx.

[18] Mathieu, J. 2012*, Modeling, Analysis, and Control of Demand Response Resources,* Lawrence Berkeley National Laboratory, LBNL-5544E; Paul Steffes, *Grid Interactive Electric Thermal Storage Water Heating* (2012); *R.* Farrell Troutfetter, *Market Potential Study for Residential Water Heater Demand Management* (March 5, 2010).

[19] Memoori. 2018. *The Internet of Things in Smart Commercial Buildings 2018 to 2022*; S. Kejriwal and S. Mahajan. 2016. *Smart Buildings: How IoT technology aims to add value for real estate companies, The Internet of Things in the CRE industry.* Deloitte University Press; S. Raschke. 2017. *IoT Enables Smart Building Technology for the Other 90%.* Available at: https://www.iotforall.com/smart-building-technology-iot-applications/amp/.

[20] Fernandez, N., Y. Xie, S. Katipamula, M. Zhao, W. Wang, and C. Corbin. 2017. *Impacts of Commercial Building Controls on Energy Savings and Peak Load Reduction.* Pacific Northwest National Laboratory. PNNL-25985.

[21] Zavalla, V. 2012. "Real-time Optimization Strategies for Building Systems," *Industrial Engineering and Chemistry Research.* Vol. 52, No. 9, 3137-3150.

[22] P. Alsone, et al. 2017. *2025 California Demand Response Potential Study: Charting California's Demand Response Future.* Berkeley, CA: Lawrence Berkeley National Laboratory.

[23] See for example: Bloomberg New Energy Finance. 2018. *Flexible Solutions for High-Renewable Energy Systems: United Kingdom.*

[24] See for example: https://www.stem.com.

optimize when isolated from the larger grid and participate in optimized grid operations when interconnected.[25]

The application distributed intelligence, enabling smart devices and systems to autonomously optimize their operation and use (production, or distribution) of energy, is a fundamental change that will occur with or without adjustments in power markets and regulation. Although its potential value is large, distributed intelligence will disrupt our current approaches for integrating demand and distributed resources and operating the power system.

In ISO/RTO and utility demand response programs, when the system operator or utility calls a demand response event, aggregators or qualified customers are paid for reducing demand from usage during a recent baseline period. This effectively assumes that baseline demand is representative of the power the customer would have used in the absence of an event being called.[26] Smart technology will anticipate demand response events and increase usage during the expected baseline period to maximize incentive payments.[27]

Time-of-Use (TOU) rates and other time-varying rate designs apply different rates in specified hours. Such rates may partially reflect variations in cost that are concealed by conventional flat rates. However, such time-varying rates will have unintended consequences in the presence of a significant number of smart devices. Intelligent devices will be aware of the time when prices change and respond with a discrete, virtually instantaneous changes in net demand. For example, with a sufficient number of vehicles using intelligent charging systems, an EV TOU rate could produce an immediate spike in demand when prices drop. This could overload distribution lines and transformers in areas where EV owners are clustered and destabilize the grid if additional supply is not immediately available.[28]

Distributed intelligence will increase system complexity. The existing power system was built on the assumption that demand would change gradually from interval to interval. This enabled regional system operators to manage the grid by dispatching large generators and controlling a limited number of flow gates, often fewer than 10,000 total points. In the near future, a single distribution utility may be connected to millions of intelligent end use devices, hundreds of

---

[25] Miller, C., M. Martin, D. Pinney, and G. Walker. 2014. *Achieving a Resilient and Agile Grid.* Arlington, VA: Cooperative Research Network, National Rural Electric Cooperative Assoc.; Kroposki, B., E. Dall' Anese, A Bernstein, Y. Zhang, and B. Hodge. 2018. "Autonomous Energy Grids," *Proceedings of the 51st Hawaii International Conference on System Sciences.*

[26] As demand response moves beyond customers with consistent daily usage, baselines become less representative of the demand that would have occurred in the absence of an event. In residential peak-time rebate programs, normal demand variability may result in as much as 40% of rebates being paid to customers who did not actively modify their consumption. Williamson, C. & Marrin, K. 2008. *Peak Time Rebate's Dirty Little Secret*. Discussion Paper presented to Association of Energy Services Professionals.

[27] While regulators may be able to identify the most blatant forms of manipulation, e.g. turning on the lights at Camden Yards during the day (*Enerwise Global Technologies, Inc.,* FERC Docket No. IN12-15-000) or turning off normally operating customer generation (*Rumford Paper Company,* FERC Docket No. IN12-11-000), intelligent systems will learn other less obvious but similarly effective strategies.

[28] M. Muratori and G. Rizzoni. 2016. "Residential Demand Response: Dynamic Energy Management and Time-Varying Electricity Pricing," *IEEE Transactions on Power Systems.* Volume 31, Issue 2.

thousands of electric vehicles, and thousands of megawatts of distributed generation and storage. Each of these autonomous intelligent devices will be responding to multiple consumer or producer objectives, optimizing its operations based in part on private information, over time scales ranging from less than 1/60th of a second (sub-cycle for AC power) to receding multi-hour time horizons, and subject to its own specific changing constraints. Centralized dispatch of such large numbers of intelligent devices may be computationally intractable within required time scales. Moreover, the lack of sufficient real-time data (including data on non-controllable loads and generation and DER controllability parameters) and insufficiently accurate system models could impede the development of optimal solutions. New approaches to market design and system operations will be needed for operators to co-optimize increasingly dynamic systems across multiple: layers (home to circuit to region), time scales (sub-cycle to multi-hour receding time horizons), and domains (buildings, transport, DER, pipelines).

Research and Development Threads

Multiple research and development projects are addressing portions of these challenges. However, it is not clear that key researchers are necessarily communicating with one another or with the system operators, utilities, regulators, and policy makers who will have to implement a roadmap for moving to a new model for power system operations.

Some of the different research and development threads that might contribute to the development of such a model include work on:

- Grid Architecture, including work on laminate architectures by Jeff Taft at PNNL and proximal messaging passing by Michael Caramanis at Boston University;
- Distributed Locational Marginal Pricing (DLMP), including work on DLMP market design by Michael Caramanis Boston University, William Hogan at Harvard, among others, and on granular DER valuation Richard Tabors at Tabors Caramanis Rudkevich, and Ralph Masiello at Quanta Technologies;
- Pricing of flexibility, including work on Hamiltonian mechanisms for pricing flexibility in high renewable energy systems by David Chassin at Stanford National Accelerator Laboratory;
- Transactive Energy, including work at PNNL, by Lynne Kiesling at Purdue, and by Anuradha Annaswamy at MIT;
- Platform markets and business models including work by Geoff Parker of Dartmouth, Marshall Van Alstyne of Boston University, and Richard Schmalensee, Emeritus at MIT;
- Future Utility Regulatory and Business Models, including work by Jesse Jenkins now at Harvard, Mark McGranaghan at EPRI, and Ignacio Pérez-Arriaga at MIT;
- Jurisdictional and legal issues, including work by Ari Peskoe at Harvard and Michael Wara at Stanford;
- Advanced applications of solid-state power electronics, including in power flow control (commercialized at Smart Wires), distribution Volt-VAr control (commercialized at

Varentec), switchable solid-state transformers, and frequency-based control in resilient communities by Deepak Divan at Georgia Tech;

- Fractal grid topologies and flexible microgrids, including work by Craig Miller at Cooperative Research Network, NRECA and Fred Wang at University of Tennessee Knoxville;
- Grid topology optimization, including work by Pablo Ruiz at NewGrid;
- Building Optimization, including work by Victor Zavala at University of Wisconsin, Johanna Mathieu at the University of Michigan, and Les Norford at MIT;
- Flexible demand, including work on demand dispatch by Sean Meyn* at University of Florida, and on gird stability and non-dispatchable price response by and Munther Dahleh at MIT;
- Data Analytics for grid forecasting and control, including work by David Culler* at U C Berkeley and Georgios Giannakis* at the University of Minnesota;
- Distributed Optimization and Control Algorithms, including work by Steven Low* at Cal Tech, Angelia Nedich* at Arizona State University; Na Li at Harvard, and Ross Baldick at the University of Texas among others;
- Controller Architecture, including work by Mihailo Jovanović* at Southern California;
- Resilience, including work by Daniel Kirschen* at University of Washington and Granger Morgan at Carnegie Mellon;
- Cyber-Physical Security, including work by Gil Zussman* at Columbia;
- Autonomous Energy Grid integration, including work by Ian Hiskens* at University of Michigan and Ben Kroposki* at NREL.

This list includes speakers at 2017 NREL Autonomous Energy Grid Conference (indicted by an *) and others whose work I have followed. It is indicative of a broad range of on-going substantive research on the future power system. However, it is not exhaustive. For example, it does not include any work on optimized EV charging, fully reflect the DOE grid modernization lab call, or the development of interoperability standards. Nor does it include representation from utilities, ISOs/RTOs, regulatory agencies, technology vendors, standards organizations, or current and former program managers for ARPA-e or other funding agencies who may have additional perspectives.

The Role of Government

Through their ability to convene parties, fund research and development, and support the development of architecture and standards, the National Institute of Standards and Technology and the Department of Energy are positioned to support collaboration among complementary initiatives, identify potential gaps and conflicts, and facilitate development of a coherent roadmap and architecture for an affordable, reliable, resilient, secure, and environmentally sustainable energy future.