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Grid 2020
Towards a Policy of Renewable and Distributed Energy Resources

Resnick Institute Report
September 2012

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The mission of the Resnick Institute is to foster transformational advances in energy science and technology through research, education and communication. The Resnick Institute strives to identify and address the most important outstanding challenges and issues in the generation, storage, transmission, conversion and conservation of energy.

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GRID 2020:
Towards a Policy of Renewable and Distributed Energy Resources

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September 2012

+ About This Report

Caltech's Resnick Sustainability Institute fosters transformational advances in energy science and technology through research, education and communication. Through its activities, the Institute strives to identify and address the most important outstanding challenges and issues in the generation, storage, transmission, conversion and conservation of energy.

To this end, the Institute provides leadership in brokering discussions on energy and sustainability issues among panels of international experts in government, academia, and industry. As part of its outreach, the Institute issues summary reports documenting these compelling events.

The Resnick Institute is solely responsible for the content of this report. The views expressed herein do not necessarily reflect the views of participants in these discussions. This report has been independently prepared by the Resnick Institute to support our efforts to communicate critical energy issues to a broad range of stakeholders.

We would like to thank the experts who contributed time and information for their willingness to engage in the candid discussions and debate that informed this report.

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Executive Summary

The transformation occurring across the world's electrical systems represents one of the greatest technological challenges industrialized societies have undertaken. Reconfiguring a grid designed to carry power one way from reliable generation sources managed by few agents to a system increasingly laden with unreliable wind and solar energy while involving millions more participants using advanced technologies will introduce a high degree of uncertainty and variability into the future grid. These changes potentially threaten reliability of electrical supply and must be carefully choreographed to avoid widespread perturbations in cost, reliability and efficiency. Yet policy mandates for more and more renewable and distributed energy resources (DER) potentially threaten to outpace the solutions necessary to manage change effectively. This report highlights critical engineering, economic and policy issues that must be addressed to ensure a successful transition. These issues arise for several reasons, including:

- Expectation of uninterrupted power reliability
- Volatility of some renewable generation and customer demand
- Time-scale alignment of customers, producers, economic and grid control actions
- Rapid changes in both energy and information technologies
- Clean energy incentives alignment with market and grid realities

Three realms in particular require focused attention on solutions. First, the transmission and distribution of electricity is fundamentally changing due to variable generation at wind and solar stations and customer load due to on-site generation and demand responses. This requires a new operating paradigm in which operational decision time cycles are decreasing beyond human capability to be central to the process as is the case today. Also, the need for coordination of transmission operations across operating regions is increasing and traditional jurisdictional boundaries between transmission and distribution are blurring. These factors combined with the massive capital investment to replace an aging infrastructure point to the need to reconsider fundamental design and operational reliability principles. The anticipated high degree of variability and uncertainty should be addressed through the use

of models and methods designed for such stochastic applications. Further, the use of related risk management techniques adapted from other mission-critical industries should be evaluated.

Second, grid operational control will be challenged due to uncertainties of intermittent energy sources as well as a profusion of dynamic data flows as control becomes more diffuse and adaptive. As such, new grid operating systems consistent with fundamental principles of control theory—observability, controllability and algorithms—are needed. Effective observability and measurement strategies are currently lacking in the industry to support needed situational awareness. Controllability across evolving market designs and grid operating systems are not yet well understood. There is an urgent need to consider the interactions across the grid and the current operational systems to ensure grid stability and reliability. Algorithms offer the promise of fast, repeatable decision routines and optimizations. A challenge is that algorithms are not easily adapted to the unique physical properties of the electric grid. Plus, system complexity is growing along with the cyber-attack surface. Architectures, design and development methods associated with ultra-large scale and complex systems are required to match the current growth trends and policy goals for renewable and distributed resources.

Third, market participation and policy support will be essential to open opportunities for business investment and innovation, yet issues of pricing schemes and market designs that properly align with grid controls, who pays and how much for critical research, infrastructure and technology are only beginning to be examined. Ideally, prices would reflect the locational value of the resource, temporal attributes consistent with the capital investment period and distribution reliability considerations. Distribution reliability considerations include distribution feeder or substation constraints, power quality and/or related operational factors. Additionally, effective market structures for distributed resources that simultaneously address distributed energy resource economics with physical distribution grid reliability considerations. However, it is not clear that current market mechanisms can replace existing transmission and distribution engineering planning, infrastructure investment decision making and cost allocation processes. Efficient and reasonable cost allocation methods are needed to address substantial distribution system investments and societal interests involving the integration of widespread distributed energy resources.

Advancements in applicable technologies and market designs that address transformation of the power system are within reach. However, the U.S. power industry is facing a post-American Recovery and Reinvestment Act funding cliff for grid modernization research, including for development and demonstration. And utility industry investment in power system research and development continues to lag due to lack of regulatory support; US utilities spend on average 0.2% of revenues on R&D—less than half as much as the comparable UK regulatory target. This percentage is even more glaring when combined with the need to replace an aging electric infrastructure grade "D+" by the American Society of Civil Engineers in their 2009 report card on America's infrastructure. Current economic conditions are a difficult environment to manage the impact of a half a trillion dollar investment in electric infrastructure underway this decade on customers' electric rates. This presents a significant challenge as polls show people are not well informed about the transformation of the power system resulting from their adoption of solar photovoltaic rooftop panels and support for clean energy policies. These factors underscore a need to gain comfort with uncertainty on the future grid while reconsidering fundamental design and operational reliability principles in the electrical system. There is also a clear need for convergence of federal and state policies, wholesale and retail markets, resource controls systems, transmission and distribution control systems and customer energy management systems to achieve the scale and scope envisioned in public policy reliably and at a reasonable price.

These changes will lead to an electrical system that functions more distributed than centralized as millions of new participants engage it in new ways. Increased transparency and cross-jurisdictional linkages between grids will be required to increase reserve capacity and prevent supply interruptions. New energy markets operating at real-time supply and demand decision points must be established and managed. As variables multiply, the future grid will become less human-controlled and more embedded with machines and sensors that have computational power to manage millions of variables simultaneously in real time. As such, this report highlights responses to the issues identified through an integrated engineering-economic systems approach that addresses the complexity of the evolving electric system.

Introduction

The electric industry, driven by 30 years of energy policy, technology and commercial innovation, is experiencing significant growth in intermittent renewable resources, responsive demand and onsite generation and customer participation in markets. These growth trends point toward a significantly different electric system by 2020 in many parts of the United States. In essence, the electric industry is transitioning from the traditional vertical structure of deterministic centralized production and operations into a more horizontal structure that is increasingly variable and distributed in terms of production and operations.

To date, 37 states representing over 80% of the US population have enacted renewable portfolio standards or goals that require 10% to 33% of energy delivered to customers by 2020. These mostly variable resources present an operating challenge since the amount of power over the next month, hour or even the next minute is generally harder to predict than power available from hydro, gas, coal or nuclear plants. While many of these renewable plants were originally interconnected to transmission systems, more recently large amounts of rooftop solar have begun to create operating and economic issues for distribution systems.

Customers are becoming active participants in electricity markets and grid operations. The adoption of onsite generation and responsive demand capabilities is allowing consumers to also provide excess energy and services into the market. This ability gives rise to a new class of customer, a "prosumer", who both produces and consumes electricity. Federal law requires grid modernization to enable an increased dependency on variable and distributed energy resources. (1) This means that existing market and grid control systems, based on traditional centralized resources and one-way distributed power flows, require new operational paradigms, systems architectures and market structures.

This report grew from discussions during the Fall 2011 Resnick Institute Workshop, "Managing Uncertainty: Incorporating Intermittent Renewable Energy Into the Power Grid," and highlights critical engineering, economic and policy issues that must be addressed to ensure that this transition is successful. These issues arise for several reasons including the following.

1. **Extreme reliability:** The power grid is extremely reliable and consumers expect it to stay that way. When a customer turns on a switch the customer expects high-quality power to flow.

2. **Volatility of some renewable generation and customer demand:** How the variability of power from a photovoltaic (PV) solar or large wind farm and customer load/supply on the grid will affect the large-scale integrated electrical system is not well understood.

3. **Time scales of economic and grid control actions:** The grid is extremely reliable because it is controlled adaptively at time scales of seconds. By contrast, contracts between load-serving entities and power generation companies last for many decades. In the coming decade millions of independent agents, individuals and devices, will make economic and control decisions at vastly different time scales.

4. **Rapid changes in technology:** The cost effectiveness of solar power has improved significantly in a few years and may well continue to improve rapidly. The technology of energy storage systems is, likewise, improving. Bulk energy contracts are made for multiple decades and during that time advances in technologies may cause seismic shifts in the energy economy.

5. **Incentives for reducing dependence on fossil fuels:** Some governments and agencies provide substantial incentives for renewable energy generation and for improving energy efficiencies of homes, offices and factories. The influence of current incentives and expectations of future incentives makes long-term analyses of markets challenging.

Going forward, there is a clear need for convergence of Federal and state policies, wholesale and retail markets, resource controls systems, transmission and distribution control systems and customer energy management systems to achieve the scale and scope envisioned in public policy. As such, this report will highlight responses to the issues identified through an integrated engineering-economic systems approach that addresses the complexity of the evolving electric system.

Transmission and Distribution

Today's grid operating system has evolved since Thomas Edison operated the first power system at Pearl Street in New York City in 1882, but its fundamental architecture and philosophy is substantially unchanged. After a century of organic growth, the U.S. electrical system serves over 144 million customers through about 6 million miles of wire and cable and some 600,000 distribution circuits originating from an estimated 60,000 substations. (2) It was designed to balance predicable electricity demand with reliable supply from central generators. Regional transmission operators and utilities substantially control infrastructure, power flows in one direction from generator to consumer and market participants remain relatively few. However, this paradigm is changing dramatically in several US states, and around the world.

Electrical transmission and distribution system design and operation will need to evolve significantly over the next twenty years to accommodate the expected variability and diversity of supply and participation. The current electrical grid is an immensely complex and vast machine, not just of wire and steel but of political jurisdictions, human values and societal needs. It is arguably the most complex machine ever invented. The scale and scope of the change needed is unprecedented for both transmission and distribution infrastructure. Much of the grid is at or approaching the end of its expected life. The Brattle Group estimated transmission and distribution infrastructure investment could reach nearly $1 trillion through 2030 in the United States while other developed countries are facing similar challenges. (3)

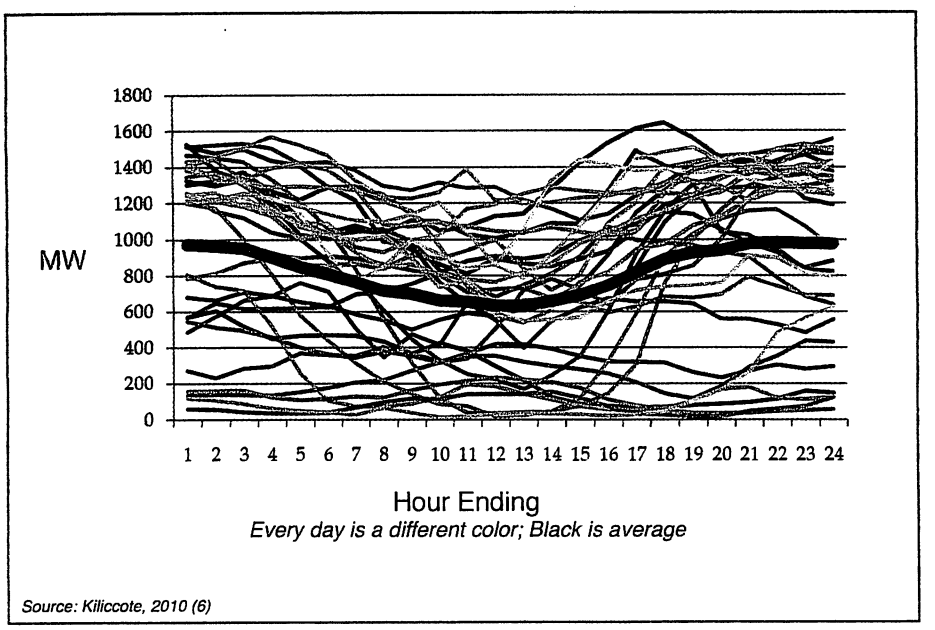
More than new steel and wires, a modern grid involves a shift in the operating paradigm on four dimensions: increased variability, shorter time cycles, resource diversity and resource dispersion. Large and small scale intermittent generation, like wind and solar PV, as well as responsive demand from EVs and smart appliances, necessitate a change from traditional deterministic to stochastic methods for planning and controls. The variability of these resources also requires faster response times for operational systems to maintain grid stability and reliability. The diversity of generation, storage and responsive demand resources connected across transmission and distribution introduce the need for greater visibility of the operations of these resources. The dis-

persion of variable and distributed energy resources across the grid irrespective of geographical and jurisdictional boundaries necessitates much greater coordination among transmission operators and with distribution operators.

Understanding Volatility

According to the Federal Energy Regulatory Commission, 37 states plus the District of Columbia have implemented renewable portfolio standards (RPS) or goals (RPG) calling for an average of about 20% energy delivered to be sourced from renewable resources by 2020. (4) These states represent about 80% of the US population. Currently 50 gigawatts of wind to meet these objectives is coming from wind farms connected at transmission. (5) The challenge for grid operations is the volatility largely associated with wind resources as depicted in Figure 1, from the CA Independent System Operator (CAISO).

Figure 1: Day to day variability of wind power generation per CAISO



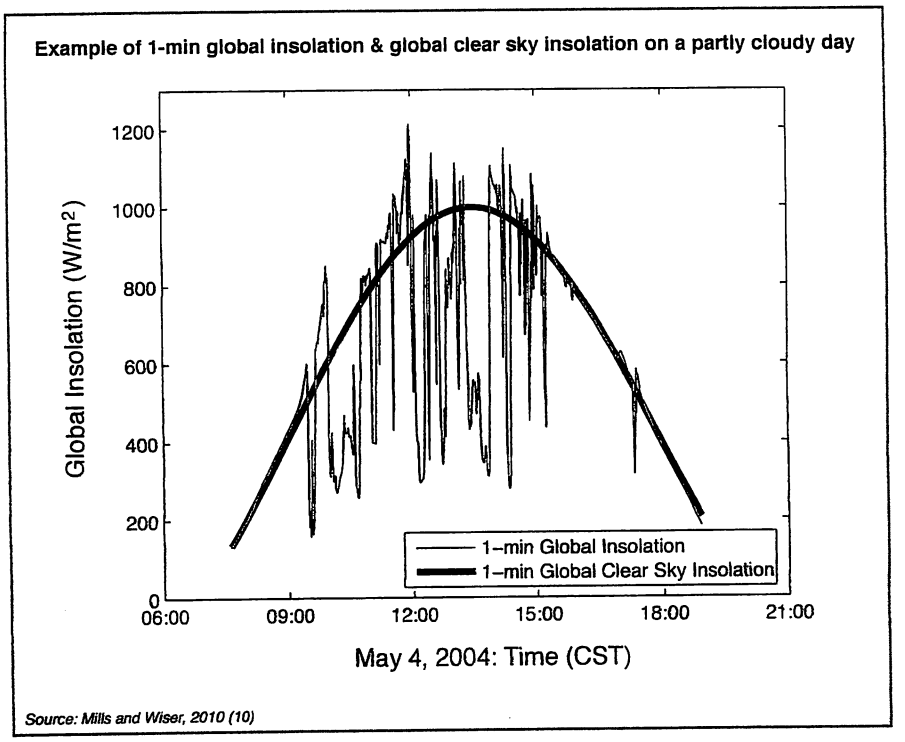
Source: Kiliccote, 2010 (6)

The minute-to-minute and day-to-day variability creates difficulties for grid operators focused on ensuring system stability. For example, as wind penetration increases, the ratio of variability to aggregate load increases and forecasting becomes harder and vulnerable to errors. Better monitoring of local wind and weather conditions for specific wind farms can improve the ability to manage minute-to-minute intermittency given some ability to leverage the rotational inertia of wind turbines to dampen sudden changes in wind speed. However, this limited dampening doesn't help with variations beyond instantaneous changes. Monitoring can also help provide better short-term wind flow predictions during a day and within an hour which also help operators manage system stability. Unfortunately, neither of these two techniques can address the fundamental variability of output and general misalignment of wind production with typical energy consumption patterns.

Meanwhile, distribution at the periphery of the electrical delivery system will undergo dramatic change due to distributed energy resources. Today, 43 states have net metering policies and 17 have added mandates or programs for solar and other distributed generation. For example, the City of Los Angeles recently approved a feed-in tariff to produce up to 150 megawatts of distributed energy in commercial properties by 2016. McKinsey recently estimated that the installed cost of solar PV could reach $0.10 per kilowatt-hour (kWh), not including margins, by 2020. (7) For comparison, the average residential electricity rate in the US in 2011 was about $0.12/kWh and commercial rate was $0.10/kWh of which 40% represents distribution and transmission costs that are expected to rise given the infrastructure investment underway. (8) As a result, Caltech research suggests that adoption of solar PV in California, which has some of the highest rates in the country, could reach between 15-50% by 2020. (9)

Distributed energy resource adoption at the levels in the analyses above will affect grid reliability in numerous ways, not all of which can be anticipated yet. What is known today is that solar PV energy production is dependent on weather conditions which are inherently changeable. This variability can create extreme changes in power output over short time periods as to create grid instability as illustrated in Figure 2. Likewise, the second-to-second changes in power output from solar PV due to clouds and humidity can introduce transients in the distribution system that can also negatively affect power quality and in some cases reliability.

Figure 2: Intraday variability in solar pv output



As such, it is critically important to understand the variability that will be introduced on the grid. Unfortunately, current planning techniques aren't equipped to assess highly volatile supply and demand resources. Historically, variability of customer demand was rather predictable based on weather and macro-economic factors. Now, demand has become more variable driven by customer micro-economic considerations like whether to charge an EV, turn off an appliance due to price signals or conserve energy to gain reward points. Traditional methods of forecasting load based on weather and macro-economic conditions will need to increasingly consider the effects of customer decision making related to consumption based dynamic micro-economic factors on near term and longer-term demand. Also, power engineering methods like transient stability, small-signal stability, and voltage stability analysis had been sufficient for system planning. Today, more sophisticated stochastic metrics and modeling techniques are needed to understand the volatility and related dynamic changes in a power system.

Operational Decisions and Coordination

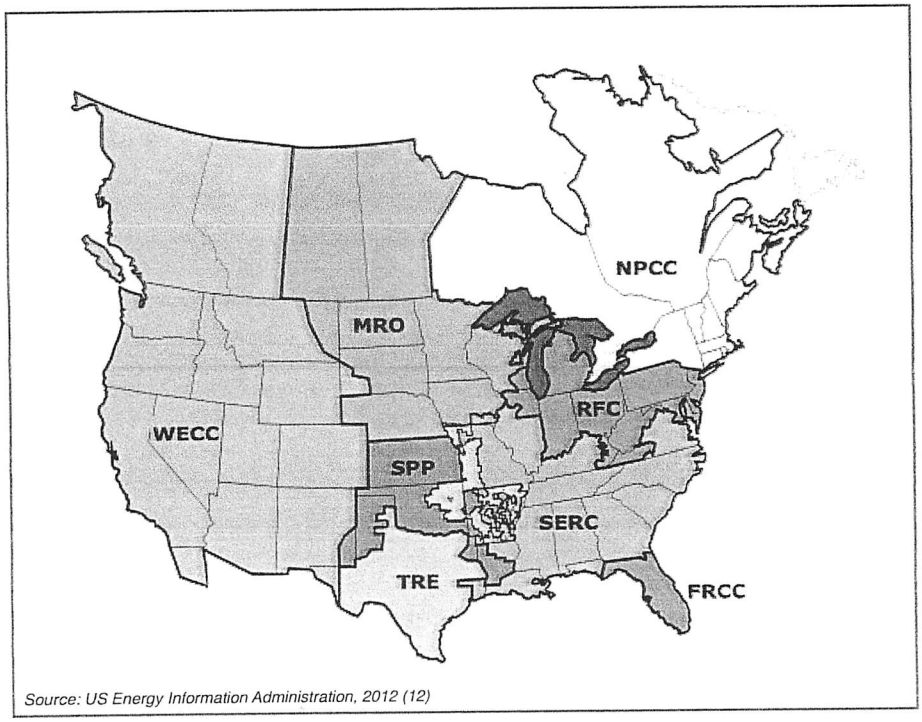
The power grid stability depends on the ability to balance demand with supply very closely, as electricity is not stored like petroleum at a gas station or tanker truck. The interrelated nature of the grid along with increasingly variability will drive the need for greater coordination between transmission and distribution operations and faster decision making to ensure reliability.

Today, this balancing occurs on standard time intervals between 5 minutes and hourly intervals based on making adjustments to generators every 4 seconds. Forecast growth in intermittent generation and highly variable loads will increase the volatility of supply and demand. The result is a reduction in the timing to balance the electric system. That is, the time to make critical operating decisions based on rapid changes in the supply and/or demand is decreasing from minutes to seconds and in some cases subsecond intervals. These shorter time scales place significant challenges for effective human interaction in the current decision processes and overall operational system.

The diversity and number of resources is projected to increase by as much as three orders of magnitude, from thousands to tens of millions. Also, these resources will be spread across the grid without regard to traditional geographical and regulatory operating boundaries. The supply-demand balance of parts of the grid is therefore complicated by the fact that a specific resource may not physically be located inside the resources' traditional jurisdictional boundary. The challenge of transmitting electricity is not limited to a single delivery system as it will be critical to improve connections across state or continental boundaries. The Tres Amigas is one approach at bridging the Western, Eastern and Texas interconnects to facilitate market transactions and related power exchange. By creating a market hub for renewable power, the Tres Amigas SuperStation will enable wind farms operating within the Texas Interconnection to export their power to California in the Western Interconnection and Chicago in the Eastern Interconnection. (11) Also, transmitting electricity across operating jurisdictions will be needed to provide reserve capacity so that production in one part of a region can support another when it loses renewable energy production due to unfavorable weather. Additionally, transmission systems lack enough coordination and transparency across

operational boundaries, which have caused grid reliability problems even with today's more predictable energy sources such as nuclear, fossil fuel combustion and hydroelectric. Greater coordination and cooperation among regional transmission operators and utility operators will be essential to reliability. As distributed resource adoption reaches significant levels on several utility systems this decade, transmission and distribution operations will also need to become better coordinated. This requires an operating paradigm shift as they have traditionally not been closely coupled since power flowed one way from transmission through distribution to customer loads. Also, better visibility of operational conditions and situational intelligence through increased sensing and real-time analytic capabilities will be required.

Figure 3: North American electric reliability regions per EIA



Source: US Energy Information Administration, 2012 (12)

Operational Risk Management

The transition from an electrical system substantially dependent on fossil fuels to one substantially powered by intermittent renewable energy represents not only technological transformation, but also a change from traditional concepts of grid reliability and stability. Operational risk management in the new paradigm may require redefinition of reliability and the methods to assess system conditions before they occur. Specifically, the increased uncertainty and complexity in the grid will require integrating stochastic approaches that also dynamically account for low probability-high impact events to power system management and decision making in control rooms. The existing paradigms of system planning, which include evaluating risk and planning for contingencies are not appropriate for a system with a high degree of uncertainty.

Traditional grid planning is based on worst case deterministic "contingency" scenarios and related risk analyses. Historic and forecasted reliability issues and associated risks are analyzed and benchmarked against historic and forecast performance. (13) This approach focuses on the loading characteristics of transmission lines, distribution feeders, substations and transformers based on forecasts of generation and customer demand. Predetermined loads and generation are analyzed to ensure that the transmission and distribution infrastructure can handle a maximum load and peak conditions for the foreseeable future—generally, the 40 year asset life of the capital investment. Today, transmission system modeling includes stochastic analysis, but not typically integrated with variable DER or distribution system analysis.

Going forward, the variable nature of renewable energy generation, EV use, DER and demand management techniques will require analyses of numerous dynamic scenarios and energy flows moving in many directions at once across distribution and transmission. Further, because of the greater amount of coupling in the system the potential for catastrophic regional blackouts will likely increase. Stochastic risk-based approaches that account for wide range of contingencies, probabilities and failure scenarios will allow for more proactive response from operators and control systems. System operation risk assessment will also need to be deconstructed at different levels leveraging techniques from enterprise risk management and perhaps quantification and valuation notions from the financial industry. A more nuanced assessment

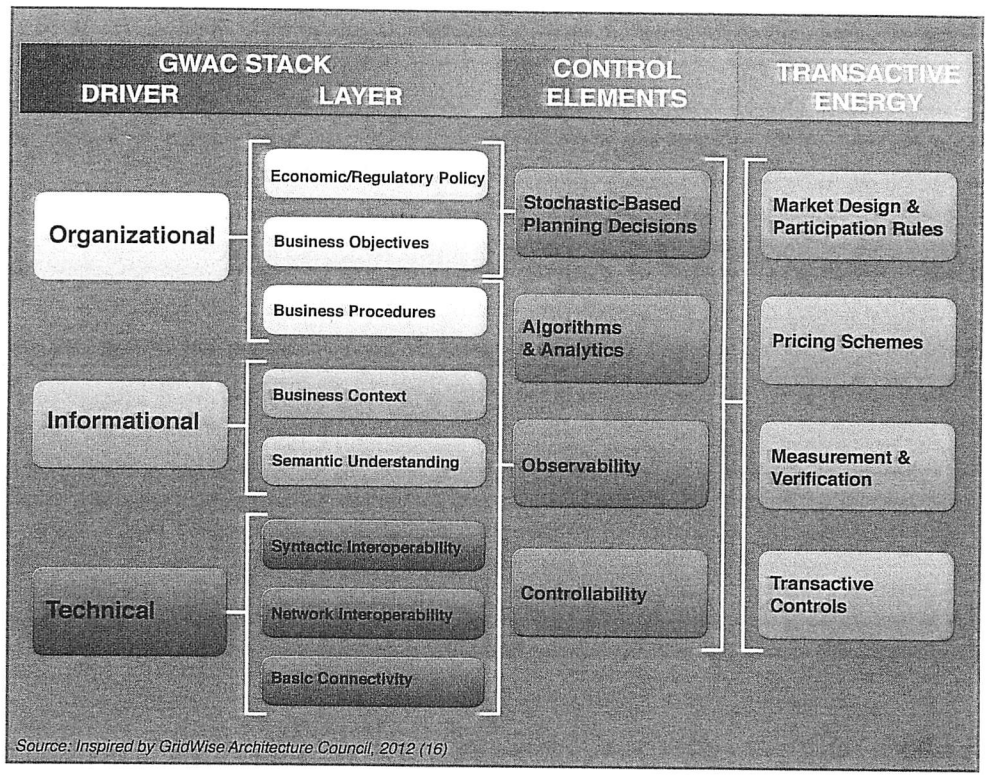
of operational risk, situation awareness and relative degrees of electric system performance may be required in the context of a hybrid system with micro-grids and a significant amount of DER. In this context, industry reliability performance criteria should evolve from deterministic to probabilistic performance criteria. These considerations may require a new conceptual or theoretical framework for managing operational risk. That is, not just look at contingencies in the face of major events but, at changes in system state and related actions that can mitigate operational risks at the cost of efficiency in current operation. These types of techniques are being applied today in several industries with critical, dynamic and complex systems such as defense, aerospace and financial markets. The parallels are quite interesting. For example, a 2007 U. S. Army Research Office report concludes, "The research has provided a scientific basis for engineering dependability in military operations with a fundamentally new approach to engineering and operation of complex informational systems for pervasive fault tolerance. Instead of specifying parameters for worst-case design of system components, these systems are designed by specifying a scalable set of resources (components) that interact to support evolving operational needs of defense applications in a dynamic and uncertain environment." (14)

In summary, grid operations in the coming decade will undergo a significant transformation due to increased variability in electric generation production from wind and solar PV resources as well as customer load becoming less predictable given onsite generation and responsive loads. These two fundamental changes to traditional supply and demand management are creating a new operating paradigm in which decision time cycles are decreasing beyond human capability to be central to the process as is the case today. Also, the need for coordination of transmission operations across operating regions is increasing and traditional jurisdictional boundaries between transmission and distribution are blurring. These factors combined with the massive capital investment to replace aging infrastructure replacement point to the need to reconsider fundamental design and operational reliability principles. The anticipated high degree of variability and uncertainty should be addressed through the use of models and methods designed for such stochastic applications. Further, the use of related risk management techniques adapted from other mission-critical industries should be evaluated.

Operational Systems

The risk of perturbations described in the Transmition and Distribution section will increase as more intermittent energy and responsive load is added to the grid, substantially increasing uncertainty. In such a dynamic system, the ability to change power outputs and demand quickly and strategically is key to providing a reliable flow of electricity. In the near future, the core challenge to managing the grid will be orchestrating numerous dynamic influences and information flows as markets and control becomes less centralized and predictable and more diffuse than today. (15) This requires the industry to evolve from systems based on deterministic, worst-case scenario planning toward dynamic operational systems based on stochastic approaches. The three pillars of control—observability, controllability and algorithms—are a helpful framework to consider the changes in operational systems. Observability relates to the situational awareness required to understand the current state and characteristics of generation output, weather conditions and consumption. Controllability of a grid laden with millions of new variables, some beyond direct control of utilities or grid operators, will require focus on information flows, new software and power management devices as well as other infrastructure components to harmonize competing priorities and ensure grid stability. Algorithms in this context include both specific operational functions in a device and analytical tools to convert data to information that is meaningful and actionable. The scale and scope of the future grid is vastly more complex than the existing electric system—already described as the most complex machine developed. In this transition, we need to chart a roadmap that reflects a prudent risk-based evolution that addresses the uncertainty related to several key decision factors.

Figure 4: Modern Grid Controls in GridWise Architecture Context



Source: Inspired by GridWise Architecture Council, 2012 (16)

Observability

The potential scale and scope of diversity requires operators and systems to have greater situational awareness to manage rapidly changing conditions effectively. Observability in this context is a measure for the effectiveness of the grid's sensor data to determine the behavior of the entire system. Variability, as described, is occurring in shorter time cycles and over massively larger footprint. This requires an observability strategy that enables visibility of grid state information in greater frequency and determining the optimal mix of data to determine the overall behavior of the electric system. These are both driven by requirements derived from protection and control systems and related market operations. It is possible to optimize the deployment of sensors and meters to achieve the necessary observability of the grid. However, it is necessary to first have a reasonable model of the system's dynamics to understand what data is needed and should be measured. Currently, the industry does not have either robust observability strategies or related measurement strategies.

A measurement strategy takes into account the real time data needs, as well as constraints on cost of implementation, and therefore takes into account the structure of the grid and markets in question. Technologies such as environmental (wind, irradiance, temperature and humidity) sensors, grid condition sensors and power measurement (phasor measurement units and energy meters) figure to play an important role. For example, phasor measurement units (PMUs) are sensors that monitor power characteristics in very small time increments—between 30 to 120 samples per second. This is a vast improvement in the fidelity of information over the traditional 4 second power measurements still widely used. Better still, PMUs data can be stamped with a time signature to synchronize the data among PMUs, creating a synchrophasor system (support for such systems to be deployed throughout the United States was included in the American Recovery and Reinvestment Act of 2009) that helps a system operator see how dynamic events, such as disruptive power oscillations caused by wind intermittency on a transmission line, unfold sequentially in real time. A utility with 50 PMUs, 2.5 million smart meters and other sensors will accumulate about 20 billion pieces of grid state data each month. This data in conjunction with appropriate controls and algorithms can allow control systems and operators to see disturbances as they begin to develop, analyze the situation in context of other grid information and take corrective action.

Controllability

In order to be able to manage the supply and demand on the electric grid, the system must be controllable. That is, the electric system stability and reliability can be maintained through the appropriate adjustment of a few input variables, like a pilot flying a plane at a desired speed, altitude and direction by manipulating the stick and rudder. This is becoming more difficult and complex as studies clearly show that dynamic wind and solar generation and responsive load on the edges of the grid will have a significant influence on grid stability at the levels targeted by public policy using only the existing grid control systems. (17) The existing grid control system is largely based on deterministic adjustment of directly controllable devices through centralized systems. Additionally, the expected scale of resource diversity and volatility may cause the electric system to become inherently unstable, not unlike a modern jet fighter that requires

sophisticated avionics to maintain stability of the inherently unstable aircraft, in addition to pilot inputs. New approaches will be therefore required.

Several challenges exist in development of new control systems and are currently being researched. Control points (generation and responsive demand) of future grid control systems are becoming more dynamic and less controllable. For example, differences in the controllability properties of variable and distributed resources differ substantially from the comparatively simple operating characteristics of traditional generation resources and aggregate load dynamics at substation and transmission system levels that have characterized the electric grid the past 40 years. Also, many of these variable resources are also not time-aligned or positively correlated with traditional supply and energy consumption patterns, adding significant complexity to the development of effective grid control systems and related markets. Another important aspect for consideration is that current operation of primary and secondary distribution networks is largely decoupled from operation (market-based and direct control) of the high- voltage transmission network. That is, the distribution system is allowed to "float," while bulk resources on the transmission side must react and adapt. In this scheme, load is measured for control purposes in the aggregate at substations as part of the feedback mechanism. Large-scale fossil-fuel, geothermal, nuclear and hydro generation plants are controllable inputs to the system that are measured closely and directly controlled. And, most of the distributed resources at the edge are not systematically measured or controllable. These have often been treated as negative values against load since total distributed generation production was relatively small.

With increased penetration of distributed energy resources such as solar PV, this approach will no longer work as additional strain will be placed on transmission side resources to compensate variability in DERs as well as physical problems on distribution circuits. There is also the potential for significant operational flexibility in the distribution system related to customer loads, which are currently underutilized, that may prove useful in buffering the effects of renewable resource variability at the bulk system level. Further research is needed to resolve the questions related to how tightly or loosely coupled distributed resources (generation, storage and demand) should be to maintain overall grid reliability and power quality. These questions involve the evolution of distributed controls from the current centralized approaches and related data

and control architectures. Perhaps it is better to loosely couple certain aspects of the grid rather than tightly interconnecting them. For example, the use of local control, as envisioned in microgrids, may reduce operational risk by minimizing the impact of local grid dynamics resulting from customer changes in energy consumption and/or production on the broader transmission system. In this context, wide area control involving tightly coupled control of distributed resources may be dangerous because it allows larger catastrophic events. Also, with appropriate observability and control latency is it possible to relax existing system tolerances such as frequency limits? These questions underlie the discussion of microgrids in a super-grid architecture. (18)

Today, the human operators play a critical role within the overall grid control system. Human interaction in decision making within a control loop is an important consideration as the system designs become reliant on the use of algorithms and expert systems through machine-to-machine interfaces. While there have been spectacular system failures in the forms of large blackouts because of human error, operators routinely provide a critical check on the system. The role of system checks, whether human or machine, is an important consideration in the discussion of centralized and distributed market designs and possible links to dynamic price signals as significant system control inputs. This is because of the potential to enable unintended effects like the financial market flash crashes that have occurred several times over the past five years. However, certain dynamic operational conditions are beginning to occur on very short time scales that are not always observable by operators and responses are required in a matter of seconds or less. There is a growing recognition that machine-to-machine-based systems leveraging expert systems and adaptive controls will be needed. So the issues also involve the changing nature of the role of human operators and appropriate automated risk management checks on future systems.

Algorithms and Analytics

The future electric system will include a large network of devices that are not only passive loads, as most endpoints today are, but can generate, sense, communicate, compute, and respond. In this context, intelligence will be embedded everywhere, from EVs and smart appliances to inverters and storage devices, from homes to microgrids to substations. This growing network of

intelligent energy devices was termed the EnerNet by Bob Metcalfe in 2008. These resources can, collectively and separately, introduce large, rapid, and random fluctuations in electricity demand, supply, and related power quality. As such, system stability may increasingly depend on complex queries among millions of grid and customer DER state data streams simultaneously to detect specified system conditions, thus triggering appropriate actions based on algorithms in real time. Traditional centralized information and control systems with passive integration of distributed resources cannot support this future electric system. Therefore, simple and scalable distributed control schemes fed by decentralized information are required to address the need to actively integrate these resources into markets and grid operations. At the heart of these essential distributed controls are algorithms that are computationally fast providing real-time feedback control within closed-loop systems to deal with random volatility.

There are three main challenges to developing algorithms for power systems. First, power systems fundamentally behave in a nonconvex manner that is very difficult to develop efficient algorithms to solve the complex optimizations required for large-scale DER adoption (convexity is the property that determines whether an efficient algorithm exists to solve a problem, and power systems are therefore difficult to solve quickly or efficiently). Second, algorithms must take into account the high degree of uncertainty and variability related to demand and supply. Unlike the current worst-case deterministic methods that address a limited set of contingencies, future algorithms will need to consider a range of operating scenarios. Also, the relationships among the various uncertainty factors will need to be considered on a large span of time and spatial dimensions. Third, electric systems with millions of customers and devices ("agents") independently and dynamically interacting with markets and grid operations is a very complex algorithmic challenge. Each DER device or customer responding to prices or control signals is an agent on the grid and/or market. The decision processes for each agent must be understood and coordinated to ensure a stable and reliable power grid. This means that grid control decisions must be made using only partial information as it is impossible to fully know all aspects of the agent's decision process. Yet, the global behavior that results from the interaction of the local algorithms in use by the agent must not only be stable, but also be

understandable. Also, the grid control algorithms must align the competing interests of multiple agents and those of third parties, such as energy services firms, that have competing interests that may influence DER operating decisions. This alignment isn't easily resolved by sending a price signal as suggested by those advocating "prices to devices."

System Complexity and Evolution

Operation of the grid in the future will almost certainly differ dramatically from the past. We are clearly evolving from a human-centric operational model to a machine-centric model, much as the aviation industry has evolved to "fly-by-wire" systems. A number of architectural issues remain to be resolved including the role of markets in grid control systems, multiple time scales, multiple granularity levels, and local versus wide-area controls. The challenge, of course, is to manage the transition and related operational and market systems in a manner that doesn't result in an unstable and unmanageable system. Anecdotal evidence from around the globe may already point to examples where increased resource volatility and complexity have exceeded existing grid systems ability to manage. The current complexity and operational instability issues facing Germany's electric system may be such an example of the challenges ahead. (19)

Today's grid control systems are centralized by design and do not actively integrate distributed resources into real-time grid controls at a meaningful scale yet. At the other end of the control spectrum is fully autonomous operation of the distributed resource. That is, the distributed resource is allowed to self-optimize through on-site local sensing, computing, communication and control with input from a market or grid operator. The likelihood is that for most of the next 20 years the electric system will evolve into a hybrid set of centrally controlled generation, storage and power management devices and a distributed set of resources managed on a more decentralized basis leveraging the self-managing capabilities of DER systems. Of course, as distributed resources increase, the need to balance these resources across the distribution system will likely give rise to the development of a distribution system control tier to complement the bulk power system control tier and the self-managing DER control tier. Algorithm design, be it for managing power quality or market operations, will start with mathematical models with global objectives. These

objectives will then be decomposed into algorithms for implementation locally at each control point at each of the three tiers. The underlying mathematical foundation, which includes the theories of control, optimization and stochastic processes, provides a holistic framework for integrating engineering, economics and regulation as well as systematic algorithm design.

This approach will achieve three benefits: the ability to control active endpoints at scale; a framework to understand their global behavior; and improved reliability and efficiency. One of the biggest challenges with large-scale systems is the difficulty in understanding their structural properties. The interactions between large numbers of local algorithms can often be fragile and cryptic. The control and optimization framework will not only lead to local algorithms with high efficiency, more importantly, it also provides a means to understand their interactions and coordinate their global behavior. Both the power and the risk of a network originate from the interconnection of local algorithms that are distributed across protocol layers in a network device and at different locations. Often, interesting and counterintuitive behaviors arise when local algorithms interact in intricate and surprising ways. Given the scale and diversity of the system, such behaviors will be impossible to discover or explain without a fundamental understanding of the underlying structure. A new mathematical framework must be developed to explore structures, clarify ideas and suggest directions to achieve efficient and robust design.

In summary, the scale and scope of dynamic and controllable resources will need to be incorporated into an overall market design and grid control schemes consistent with fundamental principles of control theory – observability, controllability and algorithms. Effective observability and measurement strategies are required to support the level of situational awareness and ensure an ad hoc proliferation of sensors and measurement devices do not flood grid operations with extraneous data that may impede real-time operations. Controllability across the evolving market designs and transmission and distribution systems are not yet well understood. There is an urgent need to consider the interactions across the grid and the current operational systems to ensure grid stability and reliability. Algorithms offer the promise of fast, repeatable decision routines and optimizations. The challenge is that algorithms are not easily adapted to the unique physical properties of the electric grid. System complexity is growing along with the cyber-attack surface.

Architecture, design and development methods associated with ultra-large scale and complex systems are required to match the current growth trends and policy goals for renewable and distributed resources.

Market Design and Pricing Policy

U.S. policy is to allow owners of distributed resources to effectively and reliably provide their services at scale, and operate harmoniously on an interconnected distribution and transmission grid. Accordingly, regulation, new business models and technology advances over the past decade have led to significant growth rates in distributed energy resources, including generation, responsive demand, energy conservation and customer adoption of industrial, commercial and residential energy management systems. The result is that several regions are reaching proposed capacity levels for distributed generation that exceed traditional operating and engineering practices for distribution systems. At the same time, policies advocating wholesale spot prices to customer devices ("prices to devices") have not adequately considered distribution system reliability impacts or relationship to distributed generation. As such, it is also not clear that current market models or regulations are entirely adequate or appropriate for the several emerging hybrid regional markets, such as California, with millions of distributed energy resources envisioned by 2020.

Current market and pricing policy and regulation applies wholesale models to distributed resources that do not reflect distribution level information related to location, reliability or power quality considerations. Different pricing schemes exist for each type of DER despite common capacity, energy and ancillary services attributes. Also, existing DER pricing schemes create open loops with respect to distribution system controls. New pricing mechanisms are needed to create effective closed loop systems that are tightly coupled with distribution control systems to ensure reliability and power quality. Distribution investment is also not currently aligned with widespread adoption and integration of distributed resources. There is a need to address both the engineering and economic considerations to ensure sufficient infrastructure investment. This includes resolving the question of who pays for the distribution system upgrade. It is recognized that considerable discussion and

research continues on these areas as the electric industry transitions from a vertical, centralized system to a more horizontal, decentralized system.

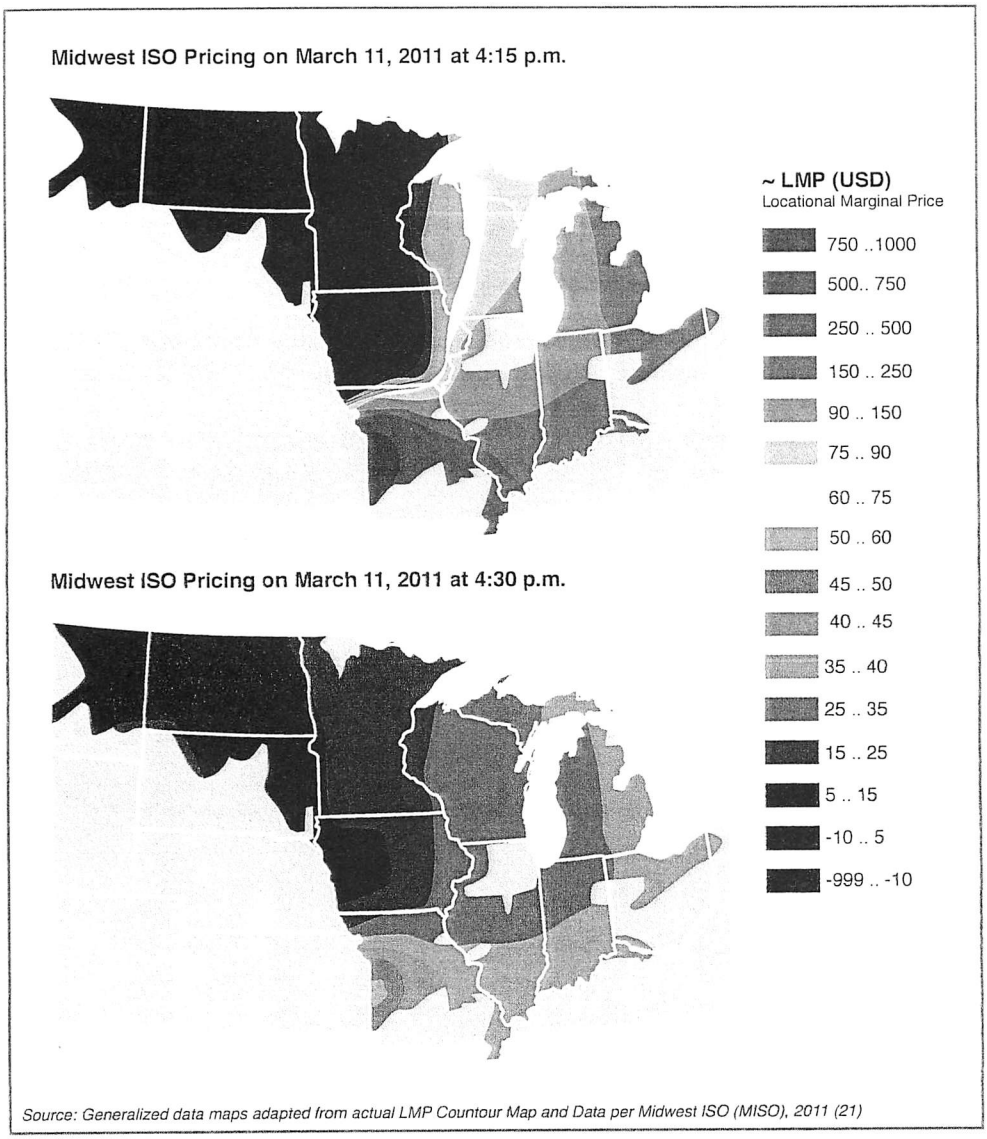
The three key areas related to markets and economics that should be addressed to achieve public policy objectives are:

1. Distributed market structure and pricing
2. Market mechanisms to ensure grid reliability
3. Distribution investment and cost allocation

Market Pricing in a Dynamic Grid

The latest stage of electricity market evolution involves a thousand-fold increase in the number of spot markets in the largest U.S. markets. This results in creation of over 20,000 Locational Marginal Pricing (LMP) nodes nationwide. The intent is to provide greater pricing fidelity to generation and transmission operation and investment decisions. LMP markets are spot markets intended to address bulk power system balancing needs that do not reflect appropriate price signals for distributed resource investment or for investment in bulk power generation resources. As such, LMP markets have made large-scale generation resource allocation on shorter time scales quite difficult as both the unit commitment problem is very hard to solve exactly, and long-term capital investment isn't driven by short-term marginal pricing. Figure 5 illustrates the effect that changes in wind have on wholesale power prices across the Midwest. The example is from a typical hour at the Midwest Independent System Operator (MISO). The two charts in Figure 5 highlight both the significant price disparity (negative prices to nearly $1,000MWh) across the region due to transmission constraints as well as the dramatic shift in prices in only 15 minutes due to changes in wind. This variability makes long term capital investment in generation and transmission very difficult. (20)

Figure 5: Locational Prices at Midwest ISO



Source: Generalized data maps adapted from actual LMP Countour Map and Data per Midwest ISO (MISO), 2011 (21)

Likewise, retail customers do not want to be exposed to this level of extreme volatility and this is why over 80% of the energy transacted in North American markets is through long-term bi-lateral contracts between producers and Load Serving Entities (LSE). These power purchase contracts typically set the price by which new generation is built. Also, the use of dynamic wholesale spot pricing, like LMP, for customer demand response, creates another challenge. Wholesale spot prices sent to customer devices inherently creates a form of decentralized real-time control, where each customer or aggregator sets device response characteristics based on their preferences. The inher-

ent closed-loop feedback between volatile spot price and aggregate demand could result in undesirable cycling of devices (and feedback into market prices). Further, these prices do not reflect distribution level information related to location, reliability or power quality considerations and will create issues for distribution systems.

Naturally, questions arise with respect to whether LMP is an appropriate market pricing mechanism for a hybrid electric system with tens of millions of distributed resource actors as envisioned by the FERC. (22) Given the growth in distributed and renewable energy adoption there is a need for consideration of market-based pricing for all distributed energy resources. Since, the potential to sell power (watts) is nearly indistinguishable from energy conservation and demand response ("nega-watts") the same fundamental price signal should be used. However, if LMP pricing is not scalable or appropriate for distributed resources, then what price and market mechanism would be appropriate to value energy at a particular point on a distribution system?

Markets generally provide a mechanism to allocate resources and enable innovation. In the electric grid over the past 20 years, deregulation and markets (spot and bilateral) have been helpful for price transparency, creating incentives for large-scale generation investment and in determining the location of new resources. Also, access to organized markets for responsive demand in several North American ISO markets, including PJM and NE-ISO, have effectively enabled innovation and a wave of demand response investment over the past decade. (23) Beyond these successes, the envisioned scale of distributed resources adds significant complexity and drives a level of convergence across the electric markets and physical operation. While this simplifies aspects of wholesale market operations, at scale this approach may result in undesirable outcomes in terms of power quality or system reliability. This is because some market designs cause the market function to act as a control element in a feedback control loop, whether intended or not. This loop is closed around a substantial portion of the power delivery system.

Ideally, prices would reflect the locational value of the resource, temporal attributes consistent with the capital investment period and distribution reliability considerations. Distribution reliability considerations include distribution feeder or substation constraints, power quality and/or related opera-

tional factors. The basic challenge resides in reliably extracting the desired response from customers on short time scales. New pricing mechanisms are needed to create effective closed loop systems that are tightly coupled with distribution control systems to ensure reliability and power quality. (24)

Market Mechanisms to Ensure Reliability

As the market adoption of DER reaches regional scale it will create significant issues in the management of the distribution system related to existing protection and control systems. This is likely to lead to issues for power quality and reliability because integrating distributed resources into wholesale markets without aligning distribution control schemes may create unacceptable consequences. (25) Consumers view reliability as a public good—they expect that whether they turn on their appliances (e.g. microwave ovens) will have no influence on the quality of power delivered to their neighbors, and no consumer is prevented from using an appliance at any time. If most of the buildings in a distribution circuit have an energy management system that turns off HVAC when electricity prices rise above a threshold, then the distribution circuit, and indeed the entire grid, can be destabilized. For example, a building manager curtailing load could inadvertently trigger a high-frequency square wave destabilizing the grid. That is, what is good for the system as a whole is not necessarily good for the feeder on my street or my power quality.

Over the last several decades, the power system had adequate generation capacity—including rapidly adaptive, load-following capacity—to ensure that supply always satisfied a generally predictable demand. Load has traditionally been viewed as deterministic and highly correlated to temperature, humidity and seasonal daylight hours. Generally, system operators could predict load with about 95% accuracy. In this electric system, extreme reliability has been achieved through adaptive real-time control by agents responsible to a centralized organization such as an ISO or utility.

This paradigm is rapidly changing due to increasing volatility in large-scale intermittent renewable resources. Plus, load is also becoming more stochastic because of onsite renewable generation and pricing schemes targeted to unlock responsiveness. As described earlier, the power grid is a dynamic system much

like an airplane. Planes use real-time information to adapt actuator settings such as engine thrust, and the manner in which this information is used by all the actuators, collectively, is critical for safety. Achieving the same degree of reliability with thousands of independent agents who respond to real time markets is a challenge.

Price signals can have an instantaneous effect on a number of independent agents, and thus the actions of one agent significantly influence the quality of power delivered to others. (26) The risk is that significant variability is being introduced that doesn't follow the traditional control system and operating paradigms. As such, the use of open loop real time prices (LMP prices to devices) will create a problem. A closed loop system of price signals aligned with market and operational factors is needed and can be effective. (27) This is also driving the need for tightly coordinated system operation for transmission and distribution. Transmission and distribution operations have traditionally operated somewhat independent of each other as power flowed in only one direction.

In addition to closed loop pricing schemes, new market mechanisms are required to ensure that the collection of independent agents will collectively adapt, in real time, to changing conditions to ensure power quality and grid stability. New operating and control systems are also needed to implement these mechanisms. Additional research into the convergence of dynamic pricing and distributed control systems is needed. There is also need for policy makers to better understand the relationship between pricing schemes and control systems as it relates to distributed energy resources to ensure proper market structures and rules to maintain a highly reliable system.

Public policy belief is that market prices will resolve not only resource allocation, but also the reliability considerations for distributed resources. That is, "prices to devices" can also ensure investment, reliability and power quality. This logic is conceptually appealing in its simplicity, however in practice at scale it becomes more challenging. It is not clear that any market has yet been able to construct an effective pricing scheme for distributed resources that can simultaneously address distributed energy resource economics with physical distribution grid reliability considerations.

Distribution Investment and Cost Allocation

Integration of widespread distributed energy resources requires reconsideration of investment and cost allocation decisions. This includes the engineering-economics of an electric distribution system. The expected increase in two-way power flows over distribution circuits will require both physical infrastructure upgrades and new intelligent distributed control systems. The significance is that an estimated $675 billion (2) will be invested in U.S. distribution infrastructure through 2030, and currently that investment is typically not aligned with federal and state energy policy supporting distributed resources. (1) Further, existing cost allocation schemes can create issues for customers seeking to interconnect distributed generation that exceeds operational limits (currently, utilities employ the "15% rule"— the aggregate distributed generation interconnected on a utility circuit shall not exceed 15% of the line section annual peak load), possibly triggering a circuit upgrade. The question of who pays for a distribution upgrade to accommodate distributed generation is not adequately addressed in most distribution planning or regulatory rate making procedures. FERC recently opened a rulemaking proceeding to consider the Solar Energy Industries Association's petition to modify interconnection rules and cost allocation. (28)

Existing distribution planning, engineering standards and related cost allocation schemes are incompatible with the scale of intermittent distributed resources targeted by energy policy. (29) So, while progress has been made on regulatory rules to encourage distributed resource interconnection in several states, there is more needed to address distribution investment. (30) Unlike transmission planning, distribution system planning does not typically involve a multi-stakeholder process that considers various proposed uses for the system before engineering is conducted and investments determined. As such, the lack of insight on the potential use of the system can lead to a systematic under valuation and investment, resulting in a failure to achieve societal needs. An early indication of the challenge is the significant growth in the backlog of distributed generation project applications. (31) For the reasons described, it is not clear that current market mechanisms can replace existing transmission and distribution engineering planning, infrastructure investment decision making and cost allocation processes.

Therefore, efficient and reasonable cost allocation schemes are needed to address substantial distribution system investments and societal interests. Estimates for fully capable distribution circuits suggest an additional cost of between $2 million and $3.5 million per circuit for physical upgrade and intelligent control systems. (32) Solar photovoltaic adoption rates by the top 15% of U.S. households and renewable portfolio targets in over 30 states representing a majority of U.S. electric demand are driving significant renewable distributed generation interconnection. It is, therefore, very possible that the incremental aggregate cost to integrate distributed renewable generation through 2030 may reach $100 billion. These upgrade costs are incremental to the Brattle capital forecast.

Who should pay for these investments? Given that energy policy, based on societal value, is driving adoption of distributed generation, perhaps all should pay. Today, however, an upgrade cost may be borne by the last increment of generation added to the distribution circuit. Another approach may be to consider incentives for third party distribution investments, not unlike merchant transmission. This may be effective for discrete assets like energy storage or power- smoothing devices, but not for transformers, poles and wires. The experience of the telecommunications industry with regard to cost allocation issues stemming from new uses of the infrastructure via "free" business models may be instructive. One lesson is to not wait until there are issues like "net neutrality" or soaring universal service costs before taking constructive action to resolve. The recent proposal by California utilities for a non-bypassable network use charge is an attempt to address these issues.

However, it is not clear that this type of proposal alone will achieve energy policy objectives or the interests of the utility. For example, non-bypassable charges may accelerate the adoption of onsite energy storage combined with solar photovoltaic systems and home energy management systems. This may make it possible for a customer to leave the grid entirely, echoing another telecom phenomenon: the rise of mobile phone service-only households, which now exceed 30% of the U.S. market, and even higher globally. The paradox is that customers leaving the grid will compound the issue of fixed cost recovery driving rates higher on a declining delivery revenue leading to potentially more customers leaving and ultimately a "death spiral". Rate redesign is needed to separate fixed costs associated with grid infrastructure

using fixed fees from variable costs like energy commodity that are more appropriate for volumetric pricing. This is essential for the economic health of the utility distribution companies as well as ensuring that costs are allocated appropriately among all users of the electric network to avoid the potential for a "clean energy divide" where those in the top income brackets avoid wires charges leaving those less able to adopt distributed generation to carry an increasingly heavy burden.

Conclusion

The electric grid of tomorrow is being built now and it will be quite different from the one that powers houses, factories and business today. The transformation is the most ambitious reconstitution of the grid since its inception more than a century ago and the change will pose serious challenges affecting all of society. This is happening worldwide due largely to legislation and regulatory mandates to increase renewable energy in response to concerns about global warming, air pollution and peak oil prices. The future grid will be more distributed than centralized as it will involve millions of new participants affecting power supply and demand. And it will convey more and more electricity from solar and wind energy sources, which are inherently intermittent and difficult to predict. Maintaining grid stability, reliable energy supplies and affordability will require solutions in technology, public policy, markets, data communications and public understanding.

It is clear the electricity grid will be unable to meet the demands of a digital society or the expansion of renewable energy without dramatic change. However, as tempting as it may be to describe the complete solution today, it is not possible given the nascent stage of many of the attributes discussed including control systems, market designs, architectures, related products and security. A number of exciting ideas and interesting demonstrations of new designs and technologies are occurring today as part of utility smart grid demonstrations worldwide. Valuable lessons are being learned from the development of these projects as well as concurrent research activities worldwide. (33) While these efforts are creating a significant foundation of knowledge about the 21st century electric system, there is much more to be learned and developed. This report highlights areas of further research

and development related to electric transmission and distribution networks, operational systems and electricity markets and pricing.

As variable and distributed energy resource adoption reach significant levels this decade, new engineering and operating paradigms are required. This may also require a new conceptual or theoretical framework for managing operational risk. Traditional deterministic methods based on worst-case contingencies will evolve to more dynamic methods to proactively respond to highly variable conditions to ensure system stability and reliability. These types of risk management techniques are being applied today in several industries with critical, dynamic and complex systems such as defense, aerospace and financial markets. Integration of resources across operating regions and significant dispersion of generation will also drive the need for greater coordination among operating regions and between transmission and distribution operations.

Distributed resources at the scale and scope contemplated by public policy will need to be incorporated into an overall market design and grid control schemes consistent with fundamental principles of control theory—observability, controllability and algorithms. Effective observability and measurement strategies are required to support the level of situational awareness required to manage the millions of distributed energy resources expected across California, for example. Controllability in the context of millions of dynamic resources in a market across transmission and distribution is not yet well understood. There is an urgent need to consider the interactions across the grid and the current operational systems to ensure grid stability and reliability. The task is daunting, however, improved decision support systems based on powerful and efficient algorithms offer the promise of fast, repeatable decision routines and optimizations. The challenge is that of adapting decision-support algorithms to meet the unique physical properties and supply/demand characteristics of the electric grid. Not surprising, system complexity is growing along with the cyber-attack surface. Architecture, design and development methods associated with ultra-large scale and complex systems are required to match the current growth trends and policy goals for renewable and distributed resources.

Advancements in information and energy technologies that build the future grid are within reach. However, the U.S. renewable energy industry is facing a post-American Recovery and Reinvestment Act funding cliff for grid modernization research, including for development and demonstration. The U.S. Department of Energy's $650 million demonstration project funds have largely been expended. And utility industry investment in power system research and development continues to lag; utilities spend an average of about 0.2% of revenues on R&D. (34) In the United States, regulators since the early 1990s have presumed that private industry will shoulder most of the R&D investment—an assumption that resulted in regulatory disallowance of most utility R&D over the past 20 years. Utilities play a critical role in new product development with technology suppliers and collaboration with research institutions. Without utility involvement, the technology development cycle significantly slows. This gap was recognized in the UK and Ofgem, the electricity regulator, has targeted R&D spending at 0.5% of utility revenues through its Innovation Funding Incentive program for distribution utilities to meet similar grid modernization goals. The question of who pays for research, infrastructure and advanced technology is not adequately addressed in most planning or regulatory rate-making procedures.

There are numerous technical and operational challenges identified in this report, but all are achievable with focus, funding and industry support. However, the most difficult gaps relate to viable business models, regulatory issues and customer acceptance. A constant refrain at smart grid conferences is the lack of viable business models in the new electricity markets. This stems in part from the scale of transformation required and the highly fragmented nature of the industry with over 3,200 utilities in the United States alone. Also, inconsistent state regulations regarding market participation and DER create significant cost barriers. Traditional jurisdictional boundaries between federal and states are becoming blurred by distributed resources in terms of reliability, operation, pricing and cost allocation. Most of the non-technical issues raised in this report require public-private dialog among FERC, state regulators and industry stakeholders to resolve.

And a glaring lack of customer awareness on the need for grid investment and appropriate cost-recovery models threatens progress toward the future grid. Transformation of the electric system will be a massive undertaking affecting

everyone, yet public education needs to substantially improve to explain the magnitude of change occurring. Over the next 20 years, the replacement of aging infrastructure and addition of advanced operational systems are guaranteed to significantly increase electricity rates. Add those costs to increased costs for change in the electrical generation mix and increased transmission investment and the challenge borne by utility customer ratepayers becomes clear. Whether the public is ready for such transformative change is less clear. The measures necessary to manage renewable energy on the grid touch on hot button issues such as rates, consumer privacy and individual choice. However, most people seem largely unaware of the changes coming. For example, a 2010 Harris Poll concluded about two-thirds of Americans have never heard the term "smart grid." (35) This gap should be addressed as an advanced grid operating system and distributed market functions will be necessary to fully utilize EVs, energy storage, demand response tools, distributed energy resources and wind farms and large solar arrays.

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