16. The economics of the smart grid technological innovation

Luciano de Castro, Joisa Dutra and Vivian Figer

1. INTRODUCTION

The power system was recently described as a "central nervous system"[1] and is in the midst of the digital revolution, driven by environmental concerns and rapidly evolving technology. The grid[2] is evolving from a one-way power flow (from central station power plants to end-users) to two-way power flow on both transmission lines and local distribution networks. Multidirectional power flows enable the development of microgrids and on-site distributed generation (DG). The timescales of power balancing have shifted from daily to second-to-second to millisecond-to-millisecond. The demands of the modern electricity system will increasingly require innovation in technologies, markets and system operations (for example, balancing authorities). The technologies that offer two-way communications and intelligent controls allow for a range of electricity services related products that rely on computer-based remote control and automation, boosting the adoption of distributed energy resources (DERs). The core of the modernization policy for the electric grid is to ensure that the electricity system is reliable, resilient and secure, while environmentally responsible at a cost-effective way. Those are the pillars of the modern electricity agenda.

Until the mid-1990s, electricity was produced and delivered to consumers by vertically integrated state-controlled monopolies (being the majority served by investor-owned utilities – IOUs), operating under cost-of-service regulation. From the 1980s onwards, mainly between 1995 and 2002 the industry went through major regulatory reform, or the "electricity restructuring." The one-way power flow and consequently solid value of its product – electricity delivered – had protected utilities from disruptive threats. The 2001 California electricity crisis and increasing environmental concerns had shifted the focus of electricity policy as technology innovation and the two-way power flow changes the role of consumers in the value network and forces utilities to review its own value proposition.

The power sector is going through a radical transformation and may be facing some disruptive threats, although it is still not clear which innovations will be disruptive. If the regulatory framework does not follow the transformation to provide incentives for efficient changing of the recovery paradigms the impact on utilities, investors and consumers will be adverse. Lessons should be learned by the deregulation in two other industries: airlines and telecommunications, which were also price regulated and capital intensive.[3] New technologies that improve the performance of a product – whether radically or marginally – consumers already know and value are called sustaining technologies.[4] They increase firm's sales to their most profitable customers, or their mainstream consumers. While disruptive technologies "introduce a different package of attributes from the ones mainstream consumers historically value,"[5] creating a new value proposition, and they generally underperform in the mainstream market in the short-term. Disruptive innovation, on the other hand, is an innovation that helps create a new market and value network. They are initially considered inferior by most in the mainstream market. Disruptive innovation shouldn't be confused with major breakthroughs, even those that change the industry's competitive patterns (Uber and Netflix).[6] The disrupter begins targeting a neglected share of consumers by the incumbent, which in turns fails to realize the innovation process in course. Eventually, the advent of a novel technology or business model allows new entrants to move upmarket and challenge incumbents with lower costs (through a disruptive path). In a 2013 report,[7] Kind argued that – probably given the low share of DERs in the national load – investors were not worried enough of the disruptive threat from these new technologies.

As extreme weather events (climate change) are becoming more frequent, policymakers also seek for new technologies that allow for fast recovery from disruptions (higher resilience). Driven by climate change[8] and the urge to decrease GHG emissions, allied with technological innovation, countries are increasing the deployment of renewable sources, especially solar and wind.

The integration of intermittent resources will also bring more complexity for the operation of the system. It will change the overall management of the network, capacity expansion and planning, as well as the economics of the power system. The intermittency inherent to these new resources comprises two distinct features: high limited-controllable variability and unpredictability. It demands a more flexible response of the power system, highlighting the importance of ancillary services. Market rules and the regulatory framework should evolve to create an environment for a new business model for delivering these services. Flexibility in the generation resources, additional operating reserves, integration of balancing areas and enhancement of balancing markets, integration of

Demand Response (DR), storage technologies, Electric Vehicles (EV) and market rules will have to be thought together to guarantee lower operation cost, market price and system stability.

Smart Grid (SG) technologies increase the visibility of the system and allow for better remote real-time monitoring and automation, data acquisition and analysis of the state of the transmission and distribution (T&D) system. For instance, advanced metering infrastructure (AMI – smart meters) combine meters with two-way communication capabilities, enabling a variety of dynamic pricing mechanisms and demand response programs. Those, in turn, can contribute in reducing the volatility of demand, the peak demand and the ability of suppliers to exercise market power. Another technology at the core of the smart grid that may change how requirements are set is the phasor measurement unit (PMU). This allows synchronized real-time measurements of multiple remote measurement points on the grid and will help balance supply and demand continuously at a lower cost upon the significant increase of intermittent generation on the high voltage network.

Widespread connection of DERs also increase digital complexity and attack surfaces, raising data security, cybersecurity and privacy-related issues. As services become more digital and automated, power disruptions have greater consequences. To unlock the potential of smart grid (SG) technologies, industry and utilities need to prepare for management and analysis of the huge amount of data that can be collected every moment. The commoditization of information arises as a strong new activity. The ability to collect and transform the data into valuable information is at the core of the smart grid transformation and in the value network of new business models to arise. The new flow of information has the potential to be disruptive to many other sectors and the workforce within them, such as building design, public safety-related services and appliance makers. Increasingly widespread consumption data also raises questions over the ownership and privacy concerns. Regulators have a key role in guiding data access by researchers and industries and maintaining privacy and security of data.[9]

The regulatory framework has to be revised to become more adaptive, allowing the innovation process to be efficient, fair and transparent. Since investing in SG technologies can either decrease operating costs or increase power quality, it is crucial to understand how the costs and benefits will be split among stakeholders: SG is not just a physical structure, but one that encompasses a range of actors and needs.[10] We discuss the smart grid, address how the policy and regulatory environment should embrace the technological changes to increase efficiency and security of the power system and the opportunities and challenges associated to the deployment of smart grid technologies at the transmission and distribution network as well as at the end-use metering level.

2. UNDERSTANDING SMART GRID

2.1 What is smart grid?

The term "smart grid" refers to a wide variety of electric grid modernization efforts and ideas, being best described as the "expanded use of new communications, sensing, and control systems throughout all levels of the electric grid."[11] It means, "computerizing" the electric utility grid.[12] The National Energy Technology Laboratory (NETL, 2009) defines five categories of smart-grid systems to describe this modernization (see also GAO, 2011):

1. integrated communications, including broadband and wireless communication
2. advanced grid components to improve system performance (smart devices such as switches, transformers, storage devices, and microgrids)
3. advanced control methods (including methods that automate distribution and locate or correct faults or potential faults)
4. sensing and measurement technologies that enable information flows from physical grid components to system operators and consumers
5. improved interfaces and decision support, which organize the information in item

Smart grid technologies are categorized by the Department of Energy[13] into customer systems (CS), advanced metering infrastructure (AMI), electric distribution systems (EDS) and electric transmission systems (ETS). Capabilities of the SG are: outage management; grid self-healing; DR; dynamic pricing; preventive maintenance of grid assets; integration of DERs and two-way communication between utilities and consumers.

According to the DOE's (2015a) Quadrennial Technology Review (QTR), technologies expected to have great impact over the next 25 years include: energy storage, distributed energy resources (DERs), variable generation resources (most notably solar and wind), electric vehicles (EVs), power flow controllers and information and processing technology.

2.2 Drivers

Driven by environmental concerns – climate change, local opposition to building new power plants and transmission lines, particulate matter, acid precipitation, water use, land and ecosystem impact – the urge to decrease GHG emissions, technological innovation and decreasing costs, countries are experiencing the increased deployment of renewable sources (especially solar and wind) and DERs. This requires more fast-acting, finer control of distribution grid operations to integrate variable, intermittent generation resources while maintaining high reliability. Big companies have already announced their intentions to run operations largely on renewables.[14] The DOE's (2015b, 2017) Quadrennial Energy Review identifies as key trends of the electricity sector: the changing generation mix; low load growth; increasing vulnerabilities to severe weather/climate change; the proliferation of new technologies, services and market entrants; increasing consumer choice; emerging cyber/physical threats; aging infrastructure and workforce and the growing interdependence of regulatory jurisdictions.

Costs for many of the emerging energy supply technologies (grid-scale batteries, solar PV, LEDs) have fallen during the last decade, although their competitiveness against conventional ones is still in progress.[15] Although some believe that even without Obama's climate regulation, state regulations may be enough for renewables to be competitive against coal.[16]

The cost of photovoltaics (PV) has declined by a factor of almost 100 times since the 1950s.[17] Solar deployment (PV and CSP) has been growing steadily. From 2009 to 2014 the compound annual growth rate was 31 percent.[18] Cost reductions of high-bandwidth communications systems are enabling more timely and granular information about conditions along power lines and within buildings.[19] The number of homes in the United States with solar PV installations grew from 15,500 in 2004 to more than 600,000 in 2014, and represents more than 80 percent of the capacity added in the past four years.[20]

The GDP X energy growth has diverged significantly across countries. Among the OECD countries, growth in GPD was associated with a slight decline in primary energy demand for the period 2000–2014.[21] Energy efficiency and the transition to a more service-based economy explain part of this trend. In less developed countries – although this trend is not yet happening – energy theft also disturbs this relation.[22] Smart grid technologies can help address both technical and non-technical loss problem with its enhanced monitoring, communication and control capabilities.

As levels of non-dispatchable resources increase, system operators have to maintain reliability while addressing the need for short, steeper ramps;

the potential for over-generation (curtailment is not readily achievable for some distributed generations) and decreased frequency response.[23] When the sun is shining, demand for utility electricity is pushed down and as the sun sets net load rises very quickly the more solar PV is deployed. The California "Duck Curve" illustrates those new needs.[24] Solar and wind are also not synchronously connected to the grid, in contrast to conventional generation, that may thus contribute to the system inertia as they can serve as baseload resources and as spinning reserves. This illustrates how the massive deployment of intermittent generation sources demands a more flexible response of the power system.

We examine the impact of the penetration of Non-Conventional Energy Resources (NCER) and DG on operation of generation plants. We look at the more technical aspects related to the security of the power system (stress of the system, voltage and frequency control, stability) and the efficient use of generation to meet demand. We discuss how the smart grid can be part of the solution for power system stability through varied control capabilities of the smart grid.[25] The adoption of new communication – sensing and control systems – allows the ISO to have real-time information on every plant operating conditions, and better remote monitor and control remotely in real time the distribution system. Other technologies, such as automatic breakers and switches accommodate significant quantities of DGs efficiently and safely. Although technology already exists for that, regulators must be active in structuring the markets to welcome new business models that unlock its potential. The evolution of the grid rests on how stakeholders and the regulatory framework evolve to provide enough financial incentives for retail consumers and service providers to make the necessary investments in new technologies.

The potential of smart grid is huge. It could reduce network operation and maintenance costs, improve reliability and resilience, integration of distributed renewable energy sources, accommodate demands for recharging of the electric vehicle of the future, expand the range of products that competing retail suppliers of electricity can offer, boosting competition and innovation in the retail sector. However, investments in smart grid technologies and its return lean on stakeholders determining the costs and benefits associated with integrating new services and technologies into the grid. It is important to understand how stakeholders and policymakers can efficiently value and integrate the services that new technologies can provide to the power system. It is not an easy task.[26] Academics and policymakers are currently actively debating how to assign these costs of intermittency to specific generators to promote incentives.[27] Deployment of ICT also requires policymakers to address privacy issues.

2.3 Challenges

The present electric power delivery infrastructure was not designed to meet the increased demands of a digital society, with increased consumer participation and share of intermittent renewable power production. The power system of the present and the future has to integrate variable power from renewable energy resources that are located within transmission and distribution systems, the two-way power and communication flows, the participation of other actors other than utilities in generation of energy, advanced communications and control technologies, cybersecurity and physical threats magnified by the increase in extreme weather events. Energy policy, regulation and markets have to provide for incentives to unlock the potential of the smart grid to resolve the challenges posed by its own adoption and ensure electricity is safely and reliably delivered in a cost-effective way. Throughout this chapter we will examine this efficient/optimal use.

The increased deployment of DERs brings the challenge of integration. They have to be connected and integrated to the grid. Otherwise, its value is not realized (provide support for grid reliability, voltage, frequency and reactive power). Experience in Germany[28] provides a useful case study regarding the potential consequences of adding extensive amounts of DER without appropriate collaboration, planning, and strategic development. Starting in 2000 a FIT program (for a period of 20 years) was set for solar power installations. In the meantime, electricity rates have increased. Increased production volume and technology advancements boosted adoption of solar PV in a self-reinforcing cycle. In addition, contrary to common sense, carbon emissions increased.[29]

For the sake of illustration, EPRI estimates that the cost of providing grid services for customers with distributed energy systems is currently about $51/month on average. In residential PV systems, for example, providing that same service completely independent of the grid would be four to eight times more expensive in the current configuration.[30]

In the absence of cost-effective storage, supply and demand must be balanced in real time. Further ahead, integration of all types of storage and other resources such as plug-in EV may become the most efficient way to counter the variability of renewables. Most analyses currently focus on the integration of renewables without the deployment of cost-effective storage on a large scale. The dissemination of such technologies will change with the diffusion of plug-in vehicles and the dissemination of cost-effective distributed storage, that will facilitate the demand and supply balance, and in the limit, electricity may be traded as other commodity. However, the important lesson to learn is the process per se – how stakeholders navigate through this transformation, with possible disruptive technologies. As described in the DOE report,[31] the grid of the future is a "tale of two timelines": the building of a "smarter grid" with the deployment of valuable technologies within the very near future or present, and the longer-term promise of "a grid remarkable in its intelligence and impressive in its scope, although it is universally considered to be a decade or more from realization."

In addition, as the number of integrated intelligent assets increase, so will the speed of required communication, coordination and control. The increasing range of "subsecond" events requires, in turn, the management of "subsecond" decisions, humanly not possible. Thus, automated (machine-to-machine) intelligence will be required. The smart grid will likely need to evolve to a smarter grid to include machine learning to manage those requirements.

The deployment of those technologies, however, faces multiple challenges, such as incentives to invest and privacy regarding the data produced. Policymakers have a key role in identifying and removing those barriers. In short, in order to take full advantage of the range of energy sources and technologies that can contribute to meeting climate change goals – such as energy efficiency; energy storage; electric vehicles; microgrids; renewable and clean energy generation – governments need to resolve institutional, regulatory and business model issues.

3. BENEFITS

The penetration of Non-Conventional Energy Resources (NCER) and Distributed Energy Resources (DER)[32] should bring challenges but have also the potential to be part of the solution for power system stability through varied control capabilities. While the current state of technology already allows for that, regulators must be active in structuring the markets to welcome new business models that create the most value as providers of this type of services. Flexibility in the generation resources,[33] additional operation reserves, integration of balancing areas and enhancement of balancing markets, integration of DERs and market rules have to be aligned to guarantee lower operation cost and system stability.

Flexibility of the power system is in the core of the debate. It requires visibility into connected resources. Advances in information and communications technologies can to enhance system visibility, understanding and control in order to improve reliability and resilience. SG technologies, such as synchrophasors and smart metering allied with data collection, analysis and transparency can provide for the required visibility across various dimensions: temporal; geographic; and analytical. It will improve evaluation of societal impacts, regulatory impacts, and of vertical industry boundaries.

3.1 Reliability and Resilience

The grid of the future will need to adapt to new technologies, threats and vulnerabilities in cost-effective ways to reach the main general goal of energy policy in most countries: the security of supply at lower GHG emission rates in an efficient way and still affordable for economically disadvantaged users. The security of supply, in turn, rests on a reliable, resilient, safe and secure grid. For the purposes of this chapter, we borrow the definition of reliability from the Quadrennial Energy Review (DOE 2017, chapter 4):

> reliability is the ability of the system or its components to withstand instability, uncontrolled events, cascading failures, or unanticipated loss of system components. Resilience is the ability of a system or its components to adapt to changing conditions and withstand and rapidly recover from disruptions. Security refers specifically to the ability of a system or its components to withstand attacks (including physical and cyber incidents) on its integrity and operations.

The growing digitalization of the economy magnifies the damage of a grid power outage (data centers). The dependence of a country in a reliable and resilience grid is magnified as homes, business and communities integrate more automated systems and technologies into their activities. The digitalization increases the economic loss of even very short power outages. The 2003 Northeast blackout affected an estimated 50 million people (61,800 MW of electric load). Current estimates for the outage-related costs that do not include extreme weather events range from $20 billion to $55 billion dollars in the US, and are increasing.[34] Although EPRI already recognized that the economic cost of power outages is largely related to the length of the outage, digitalization strengthens this relation.

However, although many metrics are available for reliability,[35] it is hard to build a standardized measure for resilience.[36] In the US, the threshold for an extended outage is five minutes, while in many European countries it is three minutes. Different metrics and different conditions (extreme weather occurrence) makes comparisons between power systems difficult. In addition, in the face of climate change, natural hazards, physical attacks, cyber threats, traditional measures of reliability based on the frequency, duration and extent of power outages seem to be incomplete to ensure system integrity and availability of electric power. It is especially challenging to measure reliability in the developing world,[37] where the efforts are usually highly concentrated in number of connections instead of power quality and reliability even though there is no evidence on how policymakers should direct their efforts.

There is no established method for quantifying the benefits of SG investments regarding reliability and resilience, with the exception of New York.[38] The provision of metrics and analytics to improve the grid's performance is included in the Multi-Year Program Plan (MYPP) of the Grid Modernization Initiative (GMI) from the Energy Department (DOE, 2015c).

3.2 Visibility and Controllability

As noted earlier, balancing supply and demand becomes more challenging as intermittent sources in the system increase. Although the undergrounding of distribution and transmission lines can contribute to improving reliability, it comes at a high cost.[39] In some cases smart grid technologies can help reduce some of its costs. As most of the infrastructure of the power system in the US is aging, and components of the system are retired, it means that newer components – often linked to communications or automated systems – are gaining momentum. The incorporation of information-processing capabilities improves controls and operations monitoring, as the system can detect and alert system operators with better precision on the location of a problem. They contribute for an optimized generation, faster diagnosis of the state of the system, and better understanding of consumer behavior.

Operators need to respond very quickly to changes in power flows at different locations on the network. As the changes in the power flow become more abrupt, operators need to hold more dispatchable generation in operating reserve status. SG technologies allow System Operators to better monitor and control adjust power flows on the T&D network to balance supply and demand at lower costs. Aligning with the propitious market configuration allows for a more efficient participation of other actors to provide electricity services.

Since smart grid technologies in the transmission and distribution network allow for better monitoring and control, they will alter network requirements, such as reducing the reserve and contingency margin needs. In the Grid Modernization MYPP (2015) it was estimated that a drop from 13 to 10 percent in the average planning reserve margin that could be achieved through the deployment of modernization technology by retailers would result in a $2 billion annual saving to the economy.[40]

With the increased visibility and controllability enabled by SG technologies, a myriad of electricity services emerges. Services that contribute to increase the economic efficiency of the grid while maintaining the security of supply at a lower GHG emission rates if the proper incentives are in place. They include activities and products with commercial value that are procured by or on behalf of electricity consumers, and vary in their nature, format and economic implications.[41]

Demand and supply must be balanced at all times to ensure system reliability (frequency must stay within a narrow band). If markets and information were perfect and free-riding did not exist, consumers and agents would create contracts to insure themselves from sudden imbalances and the markets would clear at the price of operating reserves. Given imperfections and economic (dis)incentives, regulatory intervention is necessary to insure the system reliability.

SOs set requirements to ensure that the power system operates within a certain limit. The definition of these limits and requirements (for example, the amount of needed operating reserve), and how those will be provided bring economic and engineering theory together. The need of each type of reserve (types of operating reserves depends on the quickness of response and length),[42] ancillary services, firm capacity and black start will depend on the requirements for the system flexibility that should be align to the generation mix, forecast technology, and control capabilities and the state of technology in general.[43] Regulators and System Operators have to be continuously updating such requirements as the power system is experiencing this incredible transformation.[44]

3.3 Distributed Energy Resources

Distributed generation can provide backup power to the owner of the installation, and also provide power to the SO when needed if the correct incentives are in place. It can also be used as an alternative source of power if the owner wants to maintain its electrical use and still provide energy services through demand response services if regulation prepares for that.

Demand Response (DR) has the potential to increase the volume of real-time flexible resources available, being very effective to support large-scale integration of variable renewable generation. While demand response shifts the timing of the response, storage has the potential to shift the timing of supply. As more behind the meter storage is deployed, regulators will be able to evaluate its impact on the power grid and consumer behavior. In the presence of Real Time Prices (RTP) rates, consumers or retailers may want to play the system, shifting demand through storage.

Along with other DERs, DR can also provide multiple benefits for the grid, such as the provision of firm capacity and ancillary services. For each type of DR pricing scheme (TOU, RTP, CPP, peak time rebates), the program economic impact and effectiveness relies on the adhesion policy, communication technology, market mechanisms and consumer engagement. The efficacy of the pricing scheme for reflecting the actual real-time supply/demand state of the market relies on the price interval (real-time, hourly or larger intervals) and on the lag between the announcement and implementation of prices. On the other hand, the more granular in time the price is, the higher the transaction costs for consumers. Consumers are an active and essential element of the smart grid, and the economic efficiency of the smart grid requires a comprehensive understanding of consumer types and behavior.[45] The advent of the use of behavioral science alongside economic theory has provided many advances in this regard.

Technologies enablers – smart grid and behind the meter technologies – can also play a crucial role in increasing the economic efficiency of the grid by reducing the transaction costs for consumers and reduce the trade-off between efficient pricing versus transaction costs. In the long term, the regulatory framework must aim at guaranteeing that market mechanisms provide demand response and energy efficiency enough opportunities (access, compensation and risk management).[46] Policymakers' efforts to increase investments to improve remote and automatic control of distribution and transmission networks (high and low voltage) must take into account general equilibrium results when large-scale deployment of these technologies are (to be) deployed.

Disaggregated data on the appliance level, enabled by SG technologies (consumer-based technologies) would have the ability to diagnose overconsumption and detect faulty electronics that lead to overconsumption. It will allow for quick, automatic, inexpensive diagnosis, without the need for an on-site visit by a qualified electrician.

4. COSTS, ALLOCATION AND INVESTMENTS

Financial pressures and higher risks for investors adversely affect the availability of capital. It is imperative that stakeholders have a transparent signal of how will regulatory framework will deal with the recovery cost paradigm so that the financial markets can provide clearer signals to investors. Without fundamental changes in the regulatory framework, DESs may have an adverse effect on utilities' revenues, investors' incentives and prices to end-users. If, however, we manage to mitigate cross-subsidies and provide realistic price signals we can aim at successfully supporting implementation of DERs without overburdening other customers.

Uncertainty represents another barrier for investors. In addition to the natural uncertainty in an innovation process, investors have to cope with uncertainty from the political arena, with President Trump's withdrawal from the Paris Agreement. Although some states and industries' CEOs had announced their intention to keep pursuing a clean energy future, firms in states that have strict regulations to decrease GHG emissions may have a competitive disadvantage without the support of the federal government.

Burger and Luke (2016) work on an empirical review of 144 distributed energy business models for solar PV, electricity and thermal storage and demand response, and can provide a comprehensive guide for business model (BM) options. They found that the regulatory and policy environment is a larger driver of BM structure than technology innovation. They also highlight that since BMs compete for the provision of the same electricity services, markets should allow for more competition.

As the grid is modernized and new services arise along within the change in the generation mix, it will be essential to update interconnection standards and interoperability. Wholesale market and retail rate structures have to evolve to value both capacity and energy. The lack of consolidated, enforceable standards can be a deterrent to investment. The lack of a solid and predictable framework of standards can reduce investors' willingness to take risks, since the prospect of needing to retrofit assets due changed standards turning them obsolete – reducing the benefit of a given investment. In a survey among project managers in Europe, the lack of interoperability between system elements was the most cited barrier for smart grid investments.[47]

In 2009, the US Department of Energy (DOE) launched the Smart Grid Investment Grant (SGIG) program, funded by $3.4 billion invested through the American Recovery and Reinvestment Act of 2009 (ARRA) to modernize the nation's electricity system; see US Congress (2009). Projects began in 2010, and the program was completed in 2015. The ARRA has also been identified as a key funding source for storage projects. AMI investments have also been largely driven by state legislative and regulatory requirements, as well as ARRA funding.[48] Other incentives for smart grid technology deployment for energy savings are energy conservation requirements; see FERC (2016). SG investments have the strength of a legal act, but they are not necessarily efficient, since regulators are not perfectly informed; that is, there is information asymmetry.

4.1 Cost Benefit Analysis and Allocation

Smart grid technologies are necessary as new developments require that the grid functions in ways for which it was never originally designed. As pointed out in an EPRI (2011) report, "the present electric power delivery infrastructure was not designed to meet the needs of a restructured electricity marketplace, or the increased use of renewable power production."[49]

As rates increase with the deployment of smart grid technologies, cost benefit analysis is economically and politically important. Understanding the cost and benefits is as important as informing them. In addition, since different electricity generation technologies have different temporal and spatial production profiles, valuing the cost of intermittency is per se more complex than the levelized cost framework.[50] Some researchers are addressing this issue.[51] A cost benefit analysis should be capable of taking into account the benefits it brings to the system, such as avoided build capacity and impact on transmission, distribution costs, losses and environmental value.

A better understanding of the full costs and benefits of the new services enabled by the SG will contribute to a fairer pricing structure. Currently, there is no transparent, broadly accepted framework, but progress is being made.[52] As the DOE[53] points out, it "will take time to adequately assess and validate the costs and benefits of the technology for utilities, their customers, and society."

Costs should be allocated according to benefits. The beneficiary-pays principle is not only fair, but also more efficient in determining whether an investment should be made. Those types of analyses of new technologies can't be accurate *ex ante*. As smart grid technologies are deployed, more real-world data on its costs and benefits allow for an improved evaluation along with best practice. SG technologies have the potential to improve locational signals, and contribute to a more accurate allocation on prices and estimation of beneficiaries. However, large volumes of data require good tools and highly skilled workers for data management, visualization and analytics. This estimation process is per se costly. This highlights the importance on establishing a framework or guidelines for a continuous cost benefits evaluation.

For instance, smart grid technologies may postpone or even avoid the construction of new transmission lines. Its cost benefit analysis has to take into account what are the benefits of the lines avoided. Additionally, the load benefits from increased reliability and less need of new lines (which would require costly investments). Other benefits include reduced reserve requirements, reduced energy losses, avoided project costs, improved reliability and improved access to generation resources. On the other hand, there are environmental costs from the construction of the line.

Separate transmission charges and commercial transactions are allocated *ex ante*.[54] As the deployment of grid-scale wind and solar generation in remote areas increases, the transmission grid becomes more interconnected. Therefore, the cost allocation problem is mutating. It requires continuous analysis and procedures for attracting the optimal amount and type of investment. All these points highlight the importance that detailed data on the bulk power system enabled by the new technologies should be made available to researchers.

Of course, climate policy and other policy goals (to promote a specific energy resource, universal access) result in a certain degree of cost misallocation. Renewable energy policies (RPS, FIT and cap-and-trade) are a clear illustration. In this case, transparency and predictability is of paramount importance to reduce risks and misalignment of incentives.

The costs and benefits of deploying a technology depends on scale and also on the time frame. Economy of scale and learning must be considered. Larger facilities can exploit economies of scale. Nemet (2006) found that plant size accounts for 43 percent of reduction in PV costs between 1980 and 2001. Popp (2002) uses patent data from 1970 to 1994 to estimate the effect of energy prices on energy-efficient innovations. He found a significant increase in patenting activity of around 2 percent resulting from the average change in energy prices.[55] "Learning by doing" is the cost reduction of a given technology as deployment increases and experience accumulates. Photovoltaic modules have a demonstrated a 20 percent cost reduction per kilowatt with each doubling of production over the past 40 years.[56] This brings up a chicken-and-egg problem for manufacturing: large volumes drive prices down but low prices are required to sell into the market to increase production volumes. R&D and government investment have a key role to play in the innovation process.

Note that the previous analysis does not take into account the dynamic nature of the power system. An increase in solar PV systems may increase the cost of grid integration if the higher share of intermittent generation increases the demand for ancillary services (increased backup generation and reserves' needs) and is not accompanied by other developments, such as the diffusion of demand response. In the longer-term, GHG emission targets also affect the cost of smart grid technologies. Large-scale integrated assessment models that take into account the evolution of the global energy system and climate goals to provide inputs for a longer-term assessment of DERs' cost benefit analysis.[57]

4.2 Workforce

In the previous electricity delivery framework, utilities had to send workers out to gather the data (they read meters, look for broken equipment, measure voltage). Jobs in the electricity industry require a varied range of skills. With the transformation of the grid, the set of skills required are also changing. The new business models that are and will emerge within the transformation to a smart grid will also require a new array of skills: cybersecurity concerns demand a workforce that can build and manage cyber-physical systems. The flow of data requires a workforce with high technical skills, and the increased consumer participation demands an increased participation of behavioral scientists.

One of the challenges facing the industry is the amount of time required to train new workers in response to fast changing industry needs. Another concern in the industry is retirement and the aging workforce (baby boomers and the shift from rural to urban areas).[58]

As already mentioned, solar deployment (PV and CSP) has been growing steadily. Changes in the workforce follow. From 2010 to 2015, the solar industry created 115,000 new jobs. By the end of 2014, 174,000 workers in the United States were documented as employed by the solar industry. In 2016 the solar workforce increased by 25 percent and approximately 374,000 individuals worked for solar firms.[59,60]

While over 1.9 million people are employed in jobs related to electric power generation and fuels, 2.2 million people are working in industries directly or partially related to energy efficiency.[61] RPS policies are also affecting the workforce distribution. According to DOE (2017), RPS created 200,000 gross domestic renewable energy jobs in 2013.

In addition, production and export of energy equipment represents a substantial market opportunity for the United States that would generate high-value jobs. The United States is the world's largest producer and consumer of environmental technologies: in 2015, the environmental technologies and services industry employed 1.6 million people. The Paris Agreement and increased concern with climate change will likely boost these figures.

5. WHAT ARE THE UTILITIES OF THE FUTURE?

Traditionally, utilities managed a predictable system in terms of the supply and demand of electricity with one-way flow from large, centralized generation plants to customers. The current and future delivery structure have to handle variable power from renewable energy resources that are intermittent and located within transmission and distribution systems. The two-way power flows from DERs, the active management and generation of energy by utility customers and other providers, and advanced communications and control technologies that will be more exposed to cyber and physical threats with increase the potential damage that a digitalized economy/society will face.

As DERs penetrate the system and DR and energy efficiency programs reduce the electricity demand growth, traditional utilities will play a significantly different role, and a disruptive change in the generation and electricity delivery business is likely to happen.

The two-sided flow of information and communication presents a huge potential for being disruptive to the current utilities. The smart grid technologies enable consumers to become also suppliers, more environmentally friendly and increase their ability to understand and control its electricity usage (and consequently its bill). Coupled with the current trend (and threats of climate change), electricity users are becoming more environmentally friendly. Consumers are now demanding other sources of value besides electricity. As their value proposition evolves, so do governments', whose preferences are interdependent with consumers' (voters): currently, the uptake of EV and renewables is largely driven by government policy. In this scenario, what will be utilities' value proposition?

As the two-way power flow changes the role of consumers in the value network, firms have to change their value proposition. There are many ways that the new technologies could alter firms' value proposition: integration of demand response improves balance of supply and demand, energy efficiency-related services allow consumers to decrease their bill and feel better about the environment, integration of DERs provide electricity firms with access to sources of power generation cheaper than fossil power plants. While the smart grid threatens the current business model focused on selling electricity at the lowest cost based on scale economies, it enables the integration of DERs. Besides the possibility of reducing operating costs, it also allows them to create value and respond faster to the new environmentally friendly consumers and policy requirements emerging and in transition.

The traditional utility business models rely on continued demand growth, steady economic returns and long payback horizons. The current industry structure with long-term (up to 30 years in some countries) cost recovery of investment is becoming vulnerable to cost-recovery threats from these disruptive forces. Despite the loss load due to energy efficiency and DERs that could be better handled through changes in the tariff structure,[62] some argue that this would hinder incentives for innovation by discouraging adoption of new technologies and consumer behavior focused programs.

The pace of technology changes and the uncertainty typical of an innovation process makes it especially hard to reconcile in an industry with a 30-year cost recovery of investment. It is uncertain if and when DG customers will disconnect from the grid. If the current recovery paradigm is not broken, a perverse cycle can harm utilities (as experienced in the telecom and airline industries). As DER penetrates the network, (traditional) end-users become able to control their consumption and become a supplier to the utilities. The latter however are still responsible for maintaining reliability and security of supply, providing interconnection and backup supply for variable resources, creating an additional burden on them that they pass on as costs to all consumers. This leads to higher utility rates, which in turn promotes a greater adoption of DERs, pressing the rates even more. There is much concern with the so-called "death spiral of utilities":[63] as the cost of renewables decreases, more customers leave the grid (or consume less from the grid while putting energy back into it). This pushes up grid costs for the remaining customers. Some of them will then leave the grid too, and the relative cost of producing energy versus consuming from the grid decreases even more. Realizing the high risk, investors will require a higher rate of return, and the increased cost of capital pressures rates even more.

The cost-recovery paradigm that forces the cost to be spread over all consumers would expose non-DER consumers to increasing prices. This can trigger social and political pressure to keep electricity prices artificially low – a movement that can be legitimated at the policy level. If it is not predictable how the government would react, utilities may become too exposed.

Utilities are well positioned to compete to turn into distribution platform providers as the grid changes from one-way to bidirectional power flow to accommodate DERs and alternative business models. They are uniquely positioned to collect the data, their future core business may rely less on installing the SG devices (smart meters, batteries, solar PV) and more with their connectivity. However, electricity firms should be investing in skills to make sense of big data and prepare for new players and possible disruptive and innovative business models that may emerge. Big data can be produced by the SG, to be used or sold, enabling for a myriad of new services.

This trend is already in motion: New York and Illinois started the process to allow utilities to capitalize investments in cloud-based software solutions, and the National Association of Regulatory Utility Commissioner (NARUC); issued a resolution declaring "utilities need to make the best software procurement decisions regardless of the delivery method or payment model."[64]

The New York REV Track 2 order[65] highlights the recognition and efforts by governments (regulators) to better align utility shareholder financial interests with consumer interests. It acknowledges system and energy efficiency must be at the core of the utilities business. Although utilities are still natural monopolies, their revenue streams must be tied to customers' needs. Utilities will have to operate the system by providing "distributed system platforms" to welcome third-party service providers (DER providers). The commission have been working to provide guidance for the transition.

6. HOW THE SMART GRID IS CHANGING THE ELECTRICITY DELIVERY SYSTEM

6.1 Transmission System

SG technologies have the potential to improve real time monitoring and control of the high voltage transmission network. It increases the effective capacity of the high voltage grid by reducing contingency-related congestion, and improves the network operator ability to respond to rapid and higher swings in the power flow that result from a higher diffusion of intermittent resources.

Phasor measurement unit (PMU) is one of the technologies at the core of the smart grid discussion. It is a device that measures the electrical waves on the grid using a common time source for synchronization, which allows synchronized real-time measurements of multiple remote measurement points. The resulting measurement is known as a synchrophasor. In short, it increases the visibility and awareness of the grid condition in shorter time frames, allowing operators to identify and correct for system instabilities, such as frequency and voltage oscillations. They provide data 100 times faster than conventional technology.[66] PMUs can detect the phase-angle separation, an indicator of grid stress. They form the foundation for advanced applications, such as wide-area situational awareness and state estimation, system dynamics monitoring, system model validation, and in the near future, automated response-based controls.[67] However, the density of PMUs has to be high enough to provide visibility of the entire network. Improved visibility can prevent blackouts such as the 2003 Northeast blackout that cascaded across eight states and two Canadian provinces. According to investigators of that blackout the limited visibility was one of its main causes.[68,69] This same report[70] recognized that many of North America's major blackouts have been caused by inadequate visibility of the grid, which can be improved by the deployment of PMUs.

Under the 2009 American Recovery and Reinvestment Act (ARRA), DOE supported the deployment of more than 1,300 PMUs in the US. Before the ARRA, the transmission grid had fewer than 166 PMUs.[71] By 2015, there were more than 1,700 networked synchrophasors providing visibility into transmission systems that serve about 88 percent of total US load. Although it receives a small share of the ARRA funds, according to EPRI estimates, investments in high voltage transmission networks is the most cost-effective smart grid investment.

High voltage transformers are critical to the grid and represent one of its most vulnerable components. Other benefits of the rapid deployment of PMUs upon the Smart Grid Investment Grant in ARRA are the rapid identification of failing these transformers, which can also help preventing outages. PMU data can also be used to detect a malfunctioning automatic voltage regulator controller in one generating station and failed power system stabilizers, as the New York Independent System Operator (NYISO) has experienced.

The Independent System Operator of New England (ISO-NE) can now automatically collect and analyze synchrophasor data from PMUs all across the region, enabling engineers to analyze two or three events per week (up from two events per year).[72]

Some events are too fast for human response. As data management capability improves and interventions can be automated, more outages will be avoided. The 2011 Southwest blackout, for example, may have been one of them. Cascade outages in the Pacific Southwest left approximately 2.7 million customers without power, some for up to 12 hours.[73]

The loss in the T&D system was about 6 percent from 2000–2012.[74] The rapid deployment of intermittent sources is producing power flows that the grid was built to accommodate, and increases system congestions. Over the last decade, annual congestion costs ranged between $529 million and more than $2 billion in PJM.[75]

According to a DOE report,[76] information technologies and operational strategies can help grid operators reduce losses. The same DOE report states that superconductors and power flow control technologies can reduce transmission loss by 50 percent or more, while the distribution system, reducing overloading lines through reconfiguration have identified loss reductions of up to 40 percent. The incorporation of EV charging in the dispatch algorithm also have the potential to reduce loss. Other transmission smart grid technologies are Microprocessor Based Protection, Digital Disturbance Recorders and Intelligent Electronic Devices.[77]

Congestion margins are also higher when the local system operator cannot see the state of a neighboring network, and therefore, has to be prepared for even more unanticipated events. The differences of transmission pricing and wholesale markets rules and design also increase transaction costs for the power flow between transmission networks. The SG technologies that increase the network visibility and allow for more rapid communication can improve the cost of this power flow.

6.2 Low Voltage Network

The distribution system is the most expensive part of the electricity delivery system and most difficult to upgrade and approximately 90 percent of outage minutes originate on the distribution system.[78] The deployment of SG technologies also increases the visibility and response capabilities. These technologies include automated feeder switches, capacitor controllers, fault indicators, throw-over switches and network protector monitors.[79] Integrated with sensing, communications and control technologies, they also have the potential to increase the reliability and resilience of the grid, by automatically locating and isolating faults, dynamically optimizing voltage and reactive power levels, and better monitoring of the asset conditions. Equipment health monitors can measure temperature, voltage and the levels of other parameters in transformers and other devices, giving utilities a higher level of visibility. They can help utilities reduce costs by optimizing the need for infrastructure repairs (no need for meter readers and manual disconnects). By dynamically optimizing voltage and reactive power levels, utilities can reduce power loss and deliver electricity at a lower cost. Conservation voltage reduction (CVR) also helps reduce peak demand. The result is fewer unpredictable outages and higher-quality power. The report found that CVR could result in savings of 2–4 percent on affected feeders system-wide.

Investments to increase the power quality of the grid can have an overall benefit higher that the cost. According to EPRI's estimates,[80] the deployment of technologies on the local distribution systems would cost one fourth of its overall estimated benefits. However, consumers value power quality differently (those on medical equipment, data centers and so on) and it may be more efficient to install equipment on those customer premises than making large investments on the distribution network. This would be more aligned with the beneficiary pays.

Although efforts are still in the early stages, the DOE's Smart Grid Investment Grants helped install thousands of automated feeder switches and capacitor banks. They also installed power line and equipment health sensors that have shown the potential to reduce the frequency and duration of outages, as well as to reduce energy requirements by using automated controls for voltage and reactive power management. For example, the city of Chattanooga was able to instantly restore power to half of the residents affected by a severe windstorm on July 5, 2012 (from 80,000 affected customers to less than 40,000 within two seconds) using automated feeder switching.

The uncertainty on the geographical distribution of the DG and its demands challenges the planning and operation of distribution systems. The distribution network will be required to accommodate increasing amounts of intermittent output from distributed generation resources that causes rapid variation in the demand on distribution feeders. In this case, how could regulation allow for the "cost causers" (owners of PV-DG) to bear most of the costs? Automation to upgrade distribution systems should consider DG penetration and diffusion (PV, batteries, plug-in EV) – and the resulting load placed on the system when choosing the targeted feeders.

Another challenge is how to provide price signal granular enough to account for large variations of electricity and electricity services usage. For example, in areas with a higher EV penetration, the peak demand may be late at night, when wholesale prices are low. This may place a stress on the local distribution network (which translates into a high cost) if EV owners are concentrated in a few distribution feeders.

As discussed earlier, many portions of the US electricity infrastructure (and especially the lower voltage distribution network), are aging and need to be replaced.[81] This presents a good opportunity to invest in new (and cutting-edge) technologies, since replacement investments are long-lived. But because they are long-lived, the issues raised earlier are of paramount importance when choosing how to target these investments in an economically efficient way.

Advanced communication systems with intelligent devices such as smart meters, digital controls, switches and sensors also contributes for outages managements. Advanced Metering Infrastructure (AMI) comprises smart meters, communication networks and information management systems, and it can help utilities better and faster identify an outage and disruptions, without having to rely on customers to identify flaws in the line and delivery system. However, the most praised contribution of AMIs is their ability to provide customers with information on their electricity usage and real-time pricing, helping them to manage their energy consumption more efficiently. Customer-based technologies (we also refer to them as enablers) – including in-home displays (IHD), programmable communicating thermostats (PCT), direct load control devices (DLC), building energy management systems for commercial and industrial customers

– combine with AMI to magnify its benefits. We will review in more detail the enormous range of possibilities enabled by AMI and customer-based technologies in providing the grid more flexibility, and the myriad of new business models that may arise.

There are around 58.5 million smart meters installed in the US, which represents more than 40 percent of electricity customers.[82] Among them, more than 16.3 million smart meters were deployed by SGIG utilities from 2009 to 2015 with the ARRA.

The SGIG final report states that the SGIG installed nearly 82,000 intelligent devices to upgrade about 6,500 distribution circuits. According to the report, utilities reduced the average number of affected customers by as much as 55 percent and reduced the duration by up to 53 percent using FLISR capabilities.[83] Those improvements also reduce utilities costs. The report also presents estimates on utilities savings and measures for improvement in resilience indexes (SAIDI and SAIFI) by upgrading distribution systems.

Deploying AMI with residential customer technologies can also reduce electricity demand during peak periods, resulting in more efficient use of the T&D infrastructure and investment in system replacements and upgrades. Oklahoma Gas & Electric observed up to 30 percent peak demand reduction for customers enrolled in its variable rate program.[84]

To maximize the benefits from those technologies, further advancement is needed in the management of these data. The high frequency of data, and short-time frame for response and analysis requires automated, coordinated and system-level control that is still at the academia level (research).[85]

7. MARKETS AND POLICY

Traditionally, grid operators have procured reserve generation services and charged it to the whole system, dividing the costs across all generators. Prices cannot reflect the time-varying value of power.[86] In vertically integrated markets with low intermittent generation sources this was not such an important issue, since the utility could internalize the externalities created by intermittency. Within the current market configuration, however, the failure to assign the costs of intermittency to specific generators can distort incentives.

The efforts to modernize the transmission and distribution networks and build the smart grid should be aligned with retail and wholesale market rules for better integrating demand-side management and other DERs into energy, and electricity services markets. SG technologies requires but also contribute to a better alignment of costs and prices of electricity. According to the IEA, "there is little doubt that electricity markets are needed."[87] For instance, the Chilean solar market, has been increasing very fast without any explicit tax on carbon or subsidy for renewables and in spite of low electricity prices and limited transmission capacity in part due to a free, transparent market.

Generally speaking, decentralization requires prices. As the number of DERs increase, SOs may no longer centralize all the necessary information. Therefore, electricity prices will have a key role to play in ensuring decentralized coordination.

Short-term markets are important to provide a more accurate signal for the real value of electricity. It allows market players to better manage volatilities in production and provides incentives for a more efficient adoption of DERs. A regulatory framework for the participation of other players in the ancillary services provision should also be design. FERC Order 825, issued in June 2016[88] establishes settlement interval and shortage pricing requirements for organized markets for better aligning settlement and dispatch intervals and to reflect the shortage condition. This is in order to compensate resources more accurately at prices that reflect the value of the service provided to the system.

The price of ancillary services should be the cost of the marginal resource providing the ancillary service in general, which also includes the lost opportunity cost from forgoing the energy market or other ancillary services markets.[89] Regulation should incorporate this if other actors are to participate in this market and new business models for DG, DR and DS will emerge to provide for electricity services other than energy. In the long term, the regulatory framework must aim at guaranteeing that DERs have comparable market opportunities to level the playing field. This means comparable access to markets, comparable compensation and fair and reasonable risk management.[90] There should be no functional difference between a megawatt of power from a power plant and a megawatt of reduced power from efficiency or demand response (as it is in PJM's Capacity Market).[91]

Economists should work alongside network engineering – responsible for the definition of physical network requirements standards – to design market mechanisms and provide investment incentives for the efficient adoption of smart grid technologies. They should improve the remote monitoring and control and automation of the network (distribution and transmission) as well as in technologies located in the consumer premises (smart meters and its communication capabilities). Control and regulation over wholesale prices and retail prices are among the main causes of preventing efficient pricing.[92] Market mechanisms, on the other hand, may not provide a fast enough response to unanticipated imbalances in supply/demand to achieve the network's physical operating parameters in all contingencies.

Until recently, reliability planning and operating standards and requirements set by network engineering were defined in a parallel independent process to the design and evaluation of alternative market mechanisms. As pointed out by Joskow (2008), "reliability standards and emergency protocols established by engineering have to be integrated into wholesale market mechanisms." The transition to the smart grid will also address failure of wholesale markets to provide adequate revenues to build new generating facilities to match forecasts of resource needs and help estimating consumer real marginal valuation for lost load. Electricity markets cannot optimize blackouts: there is no competitive market price during blackouts, and market mechanism cannot capture the cost of catastrophic blackouts and network collapse. Since market mechanisms in general fail to capture the expected social costs of a network collapse (because they also collapse upon a network collapse), Joskow and Tirole (2007) argue that operating reserves have a public good nature. As a result, the efficient level of operating reserves is under-provided by market mechanisms, requiring regulatory action to complement it. See also the discussion of related economic matters of de Castro and Dutra (2013).

The need for capacity market stems from several market failures. Its fundamental purpose is to provide the amount of capacity that optimizes the duration of blackouts. This is the resource "adequacy problem" (Cramton et al., 2013). The root cause of the RA problem is a pair of demand side flaws which make it impossible for the market to access, even approximately, the value placed on reliability by consumers (Cramton and Stoft, 2006). One of the possibilities enabled by the SG is the huge amount of data for understanding consumers' preferences and estimating the VOLL. As consumers take more market actions through participating in electricity services markets enabled by the SG.

Energy policy and regulation has to take into account its effects on the market. Californian power plants are estimated to be able to produce 21 percent more electricity than needed by 2020,[93] and retail electricity prices have been reported to be 50 percent higher than the rest of the United States.[94] California renewable portfolio standards (RPS) requires all firms (utilities and retailers) that sells electricity to end-users to procure an increasing fraction (33 percent by 2020, 50 percent by 2030) of this energy from renewable sources. As an increasing amount of low marginal cost energy is entering a wholesale market that already has enough energy, it pressures wholesale prices down. To support the cost of the excessive generation the gap between wholesale and retail prices increases. This illustrates the need to think the overall modernization policy altogether. The challenge is to redesign power markets to reflect the new needs for flexibility realizing new customer demands.

Incorporating externalities on prices is a hard task and subject to an ongoing debate. Economists agree that free market is not suffice to address the environmental damages of GHG emissions.[95] Pricing GHG or subsidizing green power, Feed-in-Tariffs (FIT) can be politically acceptable, but they have their drawbacks. While a carbon price increases prices in electricity markets, renewables policies and energy efficiency policies can have the opposite effect of reducing wholesale electricity prices. Pricing GHG helps all low-carbon alternatives without "putting a thumb on the scale"[96] on technologies that are still being developed and there is a lot of uncertainty regarding which one will be socially better.

The increased use of renewables increases low-carbon generation, the cap on emissions becomes easily achieved and cheap coal power plants could displace less pollutants than more expensive gas ones.

The transition to decarbonization is also challenged (or enabled) by politically motivated actors. One of the drivers of the smart grid transformation, the environmental regulations, have faced enormous political opposition. Some politicians[97] have referred to environmental regulation as "job-killing." However, empirical evidence doesn't corroborate those claims.[98] President Trump did promise that upon taking office, he'd "rescind all job-destroying Obama executive actions . . . including the Climate Action Plan."[99] On June 1, 2017 he announced his decision to pull out of the Paris climate accord. The process to exit the accord is not immediate and some analysts believe states and industries may take the lead to pursue the goals of the treaty in any case.[100]

7.1 Allocating Costs and Benefits to Value DERs – Recent Developments

The deployment and integration of DERs brings the system costs and benefits. Factors that influence the value of DERs include loss reduction, voltage control, investment deferral, environmental benefits, reliability and resilience. They can vary based on the size and location, and have to be taken into account.

Although policy in general had not kept pace with the speed of technological innovations, this is changing as more states increase their efforts to enable the deployment of new technologies and grid modernization. The majority of the reforms had been on the transition to a default time-varying rate for residential consumers.[101]

Although not expected to happen in the shorter-run, large-scale deployment of energy storage can bring disruptive changes to the power system.

Their rapid response capability makes them suited for frequency regulation and primary reserve, thus a strong competitor for ancillary service provisions. On a very large scale it can even provide electricity to the grid and displace other plants. Regulation and energy policy has to provide the correct incentives and rates to allow enough revenue streams over their working lives. Although the increasing need for flexibility creates market opportunities for storage, its high costs and the difficulties associated with quantifying the value of the array of services it provides is a major barrier. Some states are moving forward in efforts to provide a sound regulatory environment for welcoming a smarter grid.[102]

California is currently debating special rate structures for residential, commercial and industries to invest in solar PV, storage and EV. Rates with large price differentials between peak and off-peak time may hurt consumers that cannot change their consumption pattern, but may also provide financial incentives to investing in batteries for a solar PV installation or in a solar PV with storage. The options are being debated in the general rate cases (GRCs) of the state's investors owned utilities. Demand charges are also under debate and highlight the conflicts between the industry and utilities.[103]

On March 1, 2017, Arizona Public Service (APS) and solar industry representatives reached a rate design settlement[104] (to be approved by the Arizona Corporation Commission (ACC)) in which rooftop solar customers will be able to choose from four rate designs and demand charges are not mandatory, as originally requested by APS. Whatever the optimal rate design for overall welfare, it is an important step as it provides more policy stability for solar PV installers.

New York State had established a 50 percent clean energy goal within their "Reforming the Energy Vision" to "transition from the historic model of a unidirectional electric system serving inelastic demand, to a dynamic model of a grid that encompasses both sides of the utility meter and relies increasingly on distributed resources and dynamic load management."[105] The commission issued the Value of Distributed Energy Resources order establishing the rates – called the new "value of distributed energy resources" (VDER) – consists of the value of energy value, a capacity value, an environmental value and the market transition credit (MTC). Although they still need to clarify the methodology for calculating them, the uncertainty surrounding the "detail" is natural in any innovation problem, and is to be minimized if there is institutional safety backing the process. Although the commission hadn't moved away from the net-metering, it does clarify its intention to do so, as the PSC notes that retail rate net metering is "unsustainable" over the long term in New York.

8. UNLOCKING THE POTENTIAL OF SG TECHNOLOGIES

8.1 DG Solar

Solar PV plants can be installed much faster than other generation technologies. As discussed earlier, if there is a quick deployment of intermittent generation in the power system that was not adapt to incorporate it, the environmental impact and cost of electricity could be magnified.

As is the case for residential consumers' DR, many opportunities arise from the possible gains of aggregating residential consumers. The output variability of one plant is much higher than the variability of many dispersed plants – this is spatial diversification (Holttinen et al., 2013). Diversification and on-site generation contribute to a more resilient grid. The power of many small plants to improve resilience is magnified if the location and types of installation are defined in order to do so (each individual does not take into account the externalities and contribution from each own PV, only the private benefits). Thus, the aggregation of several plants can bring many benefits and a business opportunity. Welcoming this type of business model also helps avoid the problems that arise with a rapid deployment of solar PV installations.

One of the major barriers to PV adoption is the high capital costs for production and installation. There is still much to be done in terms of regulation and policy to incentivize efficient business models involving financing the installation of panels, under direct or third-party ownership. These new business models create an opportunity for investors and project developers, helping overcome the difficulties that we currently face to boost installation. The new business models that will arise depends on the fiscal incentives for installation, and market rules for the electricity produced on-site.

Customer-side business model requires a more active management of customer interface. Utilities' knowledge of their consumers puts them in a privileged position to take advantage of climate policies to provide options for DER uptake. A recent solar consumer survey exposes many possible directions:[106] solar customers are willing to help their community and contribute to the environment, even at cost; and are interested in connecting to the grid as a source of backup power and are willing to pay for it. In addition, 43 percent of people said community solar or green power plans were their preferred solar option, not rooftop PV.

Utility-side business models are also evolving alongside government clean energy policies. One type of existing business involves community solar providers installing large solar PV plants away from customers, who can buy the rights to a portion of the energy of the plant. The business charges the consumer a brokerage fee and sell the output under a long-term PPA to the regulated utility (see the Nexamp in the USA). Long-term PPAs for solar energy is used for the development of utility-scale PV finance and installation business model, where large-scale solar businesses sell the energy through PPAs and sell the renewable energy credits to a third party in the presence of a renewable portfolio standards policy.

Designing the incentives to properly remunerate solar plants is one of the main challenges faced by regulators. Researchers and regulators agree that the current net metering policies (retail net metering – RNM), where consumers are paid almost the full retail price for the energy exported into the system distorts price signals and creates cross-subsidies in favor of PV-DG users.[107] It also distorts the social value of solar relative to other renewables.[108] In fact, estimates show that these subsidies are socially regressive.[109]

Under RNM policies the PV-DG consumers export to the grid when there is excess solar energy produced and receive the full retail price, without regard to the fixed cost incurred for the distribution infrastructure (PV-DG owners do not incorporate distribution and transmission costs). In contrast to wholesale net metering, RNM is also structured with no regard to when and where (in a more granular level) the energy is produced, thus it does not provide an accurate price signal to customers. The economic inefficiencies of this policy were not a concern when the penetration of PV solar was very low and a better policy was not feasible due to meters with very little capability. In addition, implementation is administratively and technically simple. However, the perverse economic impact of increased deployment of DERs and technical improvements are leading many states to review this policy.[110]

Understanding the whole cost structure of providing electricity to end-users is the first step to efficiently allocate it. It requires assessing the cost structure, estimating the benefits for each agent and the system (which encapsulates the energy value, capacity value and reliability) and allocating it efficiently to provide incentives for investment, and for a smart use of electricity in alignment with environmental needs. Economic regulation should aim to allocate costs to beneficiaries as much as possible – to recover investments. The flat rates and price signal distortions of RNM provides incentives for panel users to maximize quantity produced regardless of the time of the day. A curious outcome of this policy is the inefficient installation of panels: if solar were paid at a time-variable rate, solar panels in the USA would generally be installed facing west, instead of south.[111]

Of course, estimating the beneficiaries and cost causers is no easy task.

Regulators and industry players should be aware of the importance of gathering data and making it available to researchers. Another (necessary) challenge is to estimate system-wide impacts: on prices (volatility and level), on competition and on job creation (direct and indirect – for instance, through the effects on the pricing structure).

Although sometimes distortive policies may be justifiable for boosting a nascent technology short-term, as was the case for solar PV, regulators should have in mind that profits must be earned, not guaranteed. It should still provide incentives for producers to become more efficient and attain grid parity.

8.2 Demand Response

According to the Federal Energy Regulatory Commission (FERC), DR can be defined as "changes in electric usage by end-use customers from their normal consumption patterns in response to changes in the price of electricity over time, or to incentive payments designed to induce lower electricity use at times of high wholesale market prices or when system reliability is jeopardized."[112]

Management of electricity consumption in response to dynamic- and location-varying spot price can reduce the peak demand and volatility of demand (and prices) and the ability of suppliers to exercise market power. It can provide the grid with the increased flexibility required to integrate intermittent energy resources and reduced costs through peak capacity reduction. The deployment of DEGs close to load centers combined with DR can also contribute to the system reliability by aiding the management of transmission congestions. In short, it is a powerful resource for a more efficient, reliable and resilient grid. Borenstein (2005) and Borenstein and Holland (2005) estimate the efficiency loss due to flat retail rates at 5 to 10 percent of wholesale electricity costs.

The smart grid relies heavily on consumer engagement. End-users can play a more active role in balancing demand and supply if they receive the correct economic incentives. There are a number of ways to increase demand participation: price-based demand response including several varying pricing schemes (TOU, CPP and RTP) and incentive-based demand response including interruptible contracts, direct load control, demand bidding and buyback, emergency demand response, capacity market and ancillary services programs.[113] There are two main categories of DR programs: dispatchable and non-dispatchable. In dispatchable programs, consumers allow an operator to control the electric appliance directly and are verifiable and capable of responding within the operator. Rates are classified according to two important characteristics: granularity – the frequency with which rates change; and timeliness – the lag between the time that a new rate is announced and the time that it is in effect.[114]

Time-of-Use (TOU) pricing is a static-time varying scheme where prices are set for predetermined hours, days and seasons. Since they don't capture the price variation within a price block (the rates are adjusted infrequently) they don't capture accurately generation costs and wholesale prices. Borenstein (2005) shows that TOU is likely to capture only a small share of the efficiency gains of RTP. However, given their more static nature, it has a lower implementation cost of implementation. Transaction costs are also minimal for this type of scheme, due to the low complexity.

Dynamic pricing schemes include Real Time Price (RTP) and Critical Peak Pricing (CPP) and may better reflect real-time variations in electricity prices and scarcity – and changes in wholesale prices and demand/supply balance. CPP is a combination of traditional TOU rates and real-time pricing. The critical peak price is designed to replace the normal peak price in order to respond to specific critical conditions (when system reliability and stability is compromised, wholesale prices are too high, or forecast of extreme weather conditions). In the short-run, the lack of dynamic pricing schemes is inefficient because consumers use more than the optimal at peak times and less at off-peak times. In the long-run it is also inefficient, since capacity-building will be above the optimal level.

Traditionally, for larger consumers, dynamic prices imply lower transaction (or relative) costs. This is because they are able to access technologies and personnel to enable demand response (energy management systems, real-time metering, and departments with skills to manage electricity consumption and participate in demand response). However, recent advances are altering the landscape: reductions in the metering installation costs, government (state) policies to increase deployment of smart meters, consumer-based technologies, the advancement in consumer behavior research and new business models with innovative solutions to promote DR (residential and industrial). Smart appliances, for instance, can be programmed to automatically adjust energy use, reducing transaction costs. Although RTP is technologically feasible, it is politically challenging: given the cross-subsidies from flat tariff rates, it may require unpopular transfer payments (Borenstein, 2007). Some argue that low-income consumers and other groups (for example, someone with medical equipment who would still have to run the equipment at peak times) would be negatively affected, given their alleged flatter pattern and more difficulty in adapting their electricity usage. According to Joskow and Wolfram (2012), recent experiences suggest that the press and consumer advocates will focus attention on those consumers. However, empirical evidence doesn't corroborate the view that low-income consumers would be adversely affected. Hledik and

Greenstein (2016) found that demand charges do not disproportionately impact low-income customers. In an earlier study, Faruqui et al. (2010a) assess three dynamic pricing programs in Connecticut, the District of Columbia and Maryland (in addition to some other results).[115] They also found that most low-income consumers would respond to dynamic pricing and benefit from it.

A commonly used and – politically more feasible – incentive-based mechanism is peak time rebates (demand-reduction programs). They provide incentives to reduce consumption during a critical event. One challenge for these programs is the lack of a reliable baseline from which to pay for the reduction and the set-up of the contrafactual to measure the impact of the program (an adverse selection problem may arise). If incentives to reduce demand are not well calibrated they may also be inefficient due to an over-reduction.[116] The long-term impacts of reward programs should also be taken into account: McClelland and Cook (1980) find that energy savings associated with reward have disappeared, and some argue they can even rebound upon withdrawal.

In interruptible contracts, direct load control (DLC) and emergency DR programs, consumers receive different types of incentives to reduce their loads. Those programs are the more efficient to quickly reduce the system load, and therefore are more fit for dealing with sudden reliability threats that price signals do not suffice (especially when prices are capped). Consumers can also offer load reduction through capacity market programs or demand bidding. Direct control programs can be more effective in the short-term, but raise more concerns regarding privacy and autonomy. In the long-term, other issues should be considered. In addition, voluntary curtailment provides the customer with many opportunities to engage in energy conservation efforts, and may consequently foster environmental identity and lead to performance of other environmentally beneficial behaviors.[117]

Aggregators and remote controlling (or some other automatic enabling technology) can help overcome the difficulties in engaging residential consumers in DR programs. Residential customers have an important role to play in demand response, especially when peak residential demand coincides with the system peak. Aggregators enroll end-users of electricity to participate in demand response and sell the combined load reduction to utilities and the ISO, and can thus spread the risk (since they build a diverse portfolio of consumers).

8.3 Consumers

For each type of scheme, the program economic impact and effectiveness will depend on: whether it is voluntary adhesion and rate of adhesion,[118] communication technology, market mechanisms and consumer engagement. It also requires a comprehensive understanding of consumer types and behavior. Borenstein (2002) shows that consumers with a flat load profile or that consume proportionally more at off-peak times will benefit the most. However, in a general equilibrium setting, consumers with a peak demand at peak hours could also benefit if incentives to reduce consumption are enough to decrease equilibrium prices at that time. In the longer run, if generation capacity investments decrease following a reduction in overall peak consumption, even those consumers can see a reduction in electricity bills. Up until recently, there was less consensus in the demand response research on whether higher peak prices simply reduce peak demand, or whether they shift the demand from peak to non-peak periods (Joskow, 2011). However, the recent fast increase in smart meter deployment accompanied by research stimulus given by the SGIG and the ARRA fund and advance the use of randomized controlled experiments informed by behavioral science is providing policymakers with an increased knowledge of consumers. Regulators, policymakers, industry and researchers are already working together to learn how deployments and pilot projects can be designed to result in higher quality evaluations. Randomized control trials[119] provide credible estimation of causal relations between policy and outcomes, although predictions based on experiments in other sites have to be carefully extrapolated.[120] As more data becomes available from (quasi) experiments and new communication technologies, program implementation and evaluation must be though together. The Department of Energy encouraged recipients of Recovery Act funding to engage in pricing experiments.[121] It is important to ensure consumers have the information and control they need to make wise decisions about their energy consumption. The degree to which demand response can be realized will be greatly affected by the willingness and ability of customers to respond to changes in price. If consumers have a low demand elasticity and generators are operating at their capacity constrain, a slight reduction in output could raise prices significantly. In electricity markets demand is too volatile and storage capacity is decreasing (this trend can revert in the longer run if cost-effective storage becomes widely available).

The smart grid affords the ability for real-time interventions and measurement. However, to unlock its potential the implementation process is crucial for a correct identification of causal effects and effectiveness of the intervention. Faruqui and Palmer (2011) access a database of dynamic rate experiments compiled by the Brattle Group with empirical data on 109 dynamic-pricing studies. They argue against the "top seven myths about residential dynamic pricing" and find that consumers do respond to higher prices by decreasing usage during peak periods. The magnitude of the response varied according to the rate designs, the availability of enabling technologies and the price rates tested. The wide variation in demand response reflects the wide variation in rate design, program implementation, underlying variation in consumer attributes and other factors. For instance, temperature may impact consumers' response to price incentives, and is important when predicting program impact based on an experiment in a different site.[122]

Technology enablers can be used to increase consumer elasticity. More granular appliance-level data can also contribute to improve forecasting-demand models, increasing the efficiency of planning and operations of SOs. There is also more evidence that households may reduce electricity consumption even in the absence of dynamic pricing if they have in-home displays and increase it upon signing up for automatic bill payment.[123] Enablers include effective real-time pricing, improved metering (lowered costs and improved functionality for meters, automated demand response technologies), energy management systems and customer displays. Bollinger and Hartmann (2015) find that households demand reduction was more than twice as large when they were given automation technology rather than technology that only informed the prices. Jessoe and Rapson (2014) designed a randomized experiment in which treatment households were exposed to a CPP plan and a subset of these households were also given an in-home display allowing them to be better informed on which appliance to turn off. They found the group with the display reduced their usage by between 8 to 22 percent on average during pricing events, up from 0 and 7 percent of the other group relative to control. They also found some evidence of habit formation, since conservation extends beyond pricing events, which is far from a consensus in the literature.[124]

Blonz (2016), studies the impacts of peak pricing in the commercial and industrial sector.[125] He uses a quasi-experimental[126] approach from Pacific Gas and Electric Company's (PG&E) "Peak Pricing" peak demand program and finds that establishments reduce their peak usage by 13.4 percent during peak hours. He finds that when PG&E calls a CPP day on hot summer afternoons, inland customers' demand reduction is larger than coastal ones' (who face more pleasant temperatures), highlighting the importance of air conditioning to dynamic price response and gives further support for enablers. Another important finding is how different types of consumers face different incentives: Blonz provides further evidence that consumer-facing establishments (theaters, restaurants) do not show a significant response to peak pricing.

Informing and educating is crucial for consumer acceptance and consequently, the program's success. The following episode highlights this challenge: after installation of the new meters as part of PG&E's Smart Meter program (Bakersfield, California) some consumers found their monthly bill doubled compared with the previous year. A class-action lawsuit was filed that questioned the devices' accuracy. PG&E concluded that the timing of installation had coincided with an increase in conventional rates, which had also coincided with unseasonably hot temperatures.[127] This illustrates that promises to consumers regarding their savings in electricity bills upon the adoption of dynamic rates may increase the credibility gap between consumers and utilities.

Until recently, policymakers, academics and stakeholders have focused on prices as the main determinant of energy demand. Some drawbacks and limitations of price-based policies have led to an increased interest in non-price energy conservation programs and behavior science.[128] The latter can be instrumental in understanding and engaging end-users to maximize the impact of SG technology. Following Sintov and Schultz (2015), electricity consumption reduction relies on consumers to undertake a series of decisions: attending to the alert; mentally cataloging energy use in home; deciding what action(s) to take to reduce energy use; executing such actions and maintaining this lower level of use over some period of time. We will go through a rich set of studies.

The Sacramento Municipal Utility District (SMUD) implemented a CPP plan, the "Smart Pricing Plan." In the plan roll-out, some randomly selected customers stayed on flat pricing while others had the time-varying option. This randomization allowed for a more accurate evaluation. Some interesting results emerged: customers on the time-varying rates cut consumption relative to the control group (peak price was $750 for 12 afternoons compared to $100 in the other days and $160 for consumers under the flat rate) as expected. Interestingly, they also did so during other days.[129] This can shed some light on how they cut their consumption. Experiments conducted by the utility provides crucial insights for program implementation. According to the "default bias" theory, when confronted by a choice in which one option is viewed as the default, people stick to that option. SMUD's customers showed this in spades: 95 percent of them stayed with time-varying pricing when it was the default, but only 18 percent chose to opt in (the selection was also random).[130] Fowlie et al. (2017) study the impacts of opt-in versus opt-out peak pricing programs (TOU and CPP). They find a significant reduction in peak electricity usage for both groups, with a larger effect for the opt-in group, as expected.

They also find that consumers on the CPP plan reduced their consumption on non-event day, which can be consistent with habit formation, fixed adjustment costs or learning. They also explore the reasons for the default bias behavior, which is crucial for understanding program welfare implications.

The new behavioral business that doesn't provide explicit control or dispatch signals is emerging.[131] They provide information and tips to consumers. An example of this type of business model is Opower. They send personal energy reports to households with information on own energy use, social comparisons (how they compare with similar households' consumption) and energy conservation information and tips. Currently, 100 utilities use the Opower platform. As of 2014, 6.2 million households were receiving home energy reports.[132]

Allcott (2011)[133] and Allcott and Rogers (2014) evaluate a series of programs run by Opower. In their home energy report letters they compared consumers' electricity use with that of their neighbors. In behavioral science it is well-documented that social comparisons induce a decrease in energy demand.[134] Allcott (2011) finds that the average program reduces energy consumption by 2.0 percent. They also find that the effect of non-price intervention is equivalent to that of a short-run electricity price increase from 11 to 20 percent, providing evidence of the cost-effectiveness of this type of model. Ayres et al. (2013) also analyze the importance of social comparisons to energy usage reduction. Using data from a large-scale, random-assignment field experiment conducted by the Sacramento Municipal Utility District they find a reduction in energy consumption of 2.1 percent in the treatment group that received periodically reports with peer comparison.

Schultz et al. (2007) reported a boomerang effect for consumers who deviated in the desired direction from the norm (that is, consuming under the desire level). In order to avoid this, they employed an injunctive norm,[135] which in this case were smiley faces on the descriptive norm feedback reports given to these relatively low users and reported it had the power to avoid the boomerang effect. Allcott (2011) also provides some evidence of the power of injunctive norms.

Allcott and Rogers (2014) find a persistence (albeit deteriorated) of the effect of home comparison reports even after they are discontinued. This persistence should be taken into account when evaluating cost-effectiveness of different policies.[136]

In order to understand this channel through which a policy intervention alters consumption decisions, Ito et al. (2015) study the effects of two types of interventions in consumers' electricity consumption at peak times: a moral suasion (intrinsic motivation) and an economic incentive (extrinsic motivation). The latter presented persistent and spillover effects (change in consumption at other than the interventions times), and the moral suasion group the persistency was large and they found no evidence of habit formation. Interventions that appeal to consumers' desire to conform with social norms may be effective for conservation purposes, but the same may not be true for peak time reductions.

Another issue raised by consumer theory is how to sell the program if consumers are expected to permanently change their consumption pattern. Self-determination theory suggests that providing reward (demand reduction programs) for behavior that might otherwise occur through intrinsic motivation (climate change, outage concerns) can weaken intrinsic motives and be counterproductive over the long-term if they undermine intrinsic motivation to act.[137] For instance, technologies that provide energy feedback at the appliance level – disaggregation technology – inform consumers exactly which appliances are consuming energy, providing them with a clear action plan, which may lead to an enhanced sense of competence or perceived control (self-determination theory and theory of planned behavior).

As we discussed, utilities can use smart grid technologies to directly control a variety of home equipment without consumer permissions or opt-out options. At first glance, this seems very effective, since it provides information on specific behaviors of the customer's electricity usage and "makes it easier" for consumers. However, although direct control technologies facilitate savings, Leijten et al. (2014) found that consumers still preferred the option of choosing how to curtail consumption. These finding are in alignment with the theory of planned behavior, which states that perceived control is an important predecessor of behavior.

In general, emerging technology faces financial, technical and social barriers. Thus, each technology should be evaluated in light of consumer behavior science to uncover the best strategies to boost adoption of such technologies. Purchasing a car or installing a solar PV panel is an infrequent behavior, so financial incentives would probably be a good strategy. Some studies have found social influence plays an important role in the installation of rooftop solar PV systems: adding a solar PV system to a single home in a neighborhood significantly increases the average number of installations within a half-mile radius (Bollinger and Gillingham, 2012; Graziano and Gillingham, 2014). These findings may help drive fiscal policy regarding DERs.

9. ADDITIONAL CHALLENGES

9.1 Jurisdictional Challenge

The three main components of the traditional power delivery system are the generation source, long-distance high voltage transmission lines and the local distribution system, where voltage has to be lowered to be carried. Electricity has traditionally been produced by large-scale generation and flowed in one direction to consumers, allowing for reasonably clear demarcations of regulatory jurisdictional and oversight boundaries. The Federal Power Act establishes the current jurisdictional divide of regulatory authority between the federal government and the states (in general, federal regulators have authority over the bulk power system and interstate commerce while state and local regulators have oversight of the distribution system and retail sales). Most European countries have a single regulatory body responsible for overseeing and maintaining reliability of the countries' power system. This division of authorities between the federal government and states is becoming more challenging with the advent of distributed generation and the two-way power flow. As DGs, distributed storage can also be interconnected with high or low voltage lines, as well as behind the meter, and along with DR, they can provide electricity services within the wholesale or retail markets for both transmission and distribution systems. Significant wholesale and retail competition in some locations among many diverse entities adds to the challenge.

The difficulty in defining the regulatory environment for DR is better exemplified by the judicial process that culminated in the Supreme Court decision ruling in favor of the FERC's authority over DR.[138] The Appeals Court decided that states had the right to regulate its utility markets.

Balancing area limits becomes also more challenging. Larger balancing areas[139] could help manage variability with an increased geographic diversity and higher aggregation of generation.[140] The integration of PacifiCorp and the California ISO Energy Imbalance Market reduced the amount of required flexibility reserves by 36 percent.[141] In addition, the lack of common principals for transmission cost allocation across regions magnifies the difficulties.

9.2 Cybersecurity and Privacy

Traditionally, reliability of the grid has mainly referred to its physical system. However, the growing digitization and reliance on data brings the information infrastructure to the core of the reliability requirements.

The increasingly widely distributed energy generation and consumption data raises questions over the ownership and privacy concerns. As services become more digital and automated, power disruptions have greater consequences. Cybersecurity threats and vulnerabilities include: physical vulnerabilities; cybersecurity vulnerabilities that refers to all the approaches taken to protect data, systems and networks; control system vulnerabilities; electrical system vulnerabilities from electromagnetic pulse; utility electricity pricing system and billing vulnerabilities; data communication vulnerabilities; privacy and data confidentiality; observation vulnerabilities.[142]

This trend exacerbates the need for regulatory standards for cybersecurity, privacy and coordination to combat threats and information sharing.[143] Utilities' challenge in securing their information and operation technology systems is magnified by their dependence on each other: "systems are only as strong as their weakest links."[144]

The increased amount of information on consumers also raises privacy concerns and the need to create privacy guidelines. Both standards and guidelines cannot be in conflict. Cybersecurity regulations needs some degree of flexibility to keep pace with evolving threats, which poses the challenge of building a transparent regulation that can evolve in the same pace of threats, as in the case of regulations for embracing the smart grid in general. As more "cloud-based" services and cloud computing for data storage and processing are employed, new cybersecurity methods have to be required.

The December 2015 cyberattack on the Ukrainian power grid demonstrated how exposed utilities are, the impact size and increased stakeholders' concerns. Security issues were the most pressing concern according to the latest Utility Dive's 2017 State of the Electric Utility Survey, after being ranked sixth in the previous years.[145] Although there had been no devastating cyberattacks against US utilities,[146] the same Russian hacker may be involved in both the attack on the Ukrainian grid and the hacking of Hillary Clinton during the 2016 presidential election.[147] The estimated economic impact of a cyberattack on the US grid is also huge:[148] $243 billion if 50 out of the 676 large generators were disabled (plus insurance claims costs). Given the high connectivity of the grid, it is crucial that everyone connected to the electric grid adhere to minimum cybersecurity standards.

The dissemination of DERs and ICTs can also be part of the solution against cyber threats if the current network topology extends optimally to integrate microgrids at the customer or community level: it can help isolate failures, provide alternative pathways for avoiding component failures, resolve local failures before the entire network is exposed to instability, and maintain continuity of service and assist in black start with the use of “islanding” operations.[149]

The valuation of DERs also needs to take cybersecurity into account in two dimensions: the process of pricing and the price itself. DERs participation in the price formation requires digital connections, and pricing and accounting systems need to be protected and monitored. This protection, in turn, costs, and needs to be recovered.

NOTES

1. Kelly-Detwiler (2015).
2. Following the DOE (2015b), the grid comprises of six elements: generation, transmission, distribution, storage, information infrastructure and demand.
3. Major carriers faced bankruptcy after deregulation while the services (fixed telephone lines) in the telecom sector had radically changed.
4. See Christensen, 1997.
5. Bower and Christensen, 1995.
6. Christensen et al. (2005).
7. Kind (2013).
8. IPCC (2014) “Climate change 2014 synthesis report,” available at http://www.ipcc.ch/report/ar5/syr/, accessed November 28, 2017.
9. ACEEE (2016) “Energy usage data access: A getting-started guide for regulators,” available at http://aceee.org/sector/state-policy/toolkit/data-access, accessed November 28, 2017.
10. E. Ela and B. Kirby (2008) “ERCOT event on February 26, 2008: Lessons learned,” National Renewable Energy Laboratory, July.
11. MITEI (2011) “The future of the electric grid,” available at http://energy.mit.edu/research/future-electric-grid/, accessed November 28, 2017.
12. Office of Electricity Delivery & Energy Reliability (n.d.) “Grid modernization and the smart grid,” available at http://energy.gov/oe/services/technology-development/smart-grid, accessed November 28, 2017.
13. Department of Energy (DOE) 2012.
14. U. Hölzle (2016) “We’re set to reach 100% renewable energy — and it's just the beginning,” Google Blog, December 6, available at https://blog.google/topics/environment/100-percent-renewable-energy/, accessed Novem ber 28, 2017.
15. IEA (2016a).
16. https://www.greentechmedia.com/articles/read/wind-is-killing-coal-in-America.
17. Nemet (2006).
18. DOE (2017).
19. DOE (2015a).
20. DOE (2015a).
21. IEA (2016a).
22. According to Giordano et al. (2013) electricity losses in LAC were 17 percent in 2007–2011 compared to 6 and 8 percent in high-income countries of the OECD.
23. System frequency must be managed to balance supply and demand of electricity at all times. While conventional generation are synchronously connected to the grid, they serve as baseload resources and as spinning reserves to provide system inertia.
24. NERL (2015).
25. Maintaining system reliability, providing real-time control of voltage.

26. For starters, electricity generation technologies have different temporal and spatial production profiles.
27. Borenstein (2012).
28. Richter (2013).
29. The environmental externalities benefits are far too difficult to measure, but still invoked as a reason to promote solar (and other clean) energy.
30. EPRI (2011).
31. DOE (n.d.) “The Smart Grid: an introduction,” available at https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_SG_Book_Single_Pages%281%29.pdf, accessed November 28, 2017.
32. DERs are smaller power sources that can be aggregated to provide power and include Distributed Generation (DG), Distributed Storage (DS), Electric Vehicle (EV) and Demand Response (DR).
33. Eureletric (2014) defines flexibility as “the modification of generation injection and/or consumption patterns in reaction to an external signal (price signal or activation) in order to provide a service within the energy system. The parameters used to characterize flexibility in electricity include: the amount of power modulation, the duration, the rate of change, the response time, the location etc.” Following NERC (2016), there are different capabilities for flexibility: ramping of the variable generation, regulating and contingency reserve, reactive power reserve, quick start capability, low minimum generation level, ability to frequently cycle the resources’ output, operation of structured markets, shorter market scheduling interval, DSM, reservoir hydro system, energy storage and improved wind and solar forecast techniques.
34. Campbell (2012).
35. System Average Interruption Duration Index (SAIDI), the Customer Average Interruption Duration Index (CAIDI) and the System Average Interruption Frequency Index (SAIFI), which measures the average number of times that a customer experiences an outage during the year (SAIFI is calculated by dividing SAIDI by CAIDI).
36. The Grid Modernization Laboratory Consortium is launching the “Foundational Metrics Analysis project” aiming to develop some standardize resilience metrics.
37. Taneja (2017).
38. DPS (2015a) CASE 14-M-0101 “Proceeding on motion of the commission in regard to reforming the energy vision: Order establishing the benefit cost analysis framework,” May 29, http://www3.dps.ny.gov/W/PSCWeb.nsf/All/C12C0A18F55877E785257E6F005D533E?OpenDocument, accessed November 28, 2017.
39. Estimated to be ten times more expensive than overhead cables: https://ucononline.com/2010/06/14/underground-electric-transmission-installations-gaining-traction/.
40. Grid Modernization Multi-Year Program Plan, 2015.
41. For a more detailed characterization of those see Pérez-Arriaga et al. (2011).
42. See Ela et al. (2011b) for a review of reserve types.
43. See Pérez-Arriaga (2011) for the needs of reserve with the penetration of intermittent in the power system.
44. Pérez-Arriaga et al. (2016).
45. See Borenstein et al. (2002), Faruqui and Sergici (2009) and Borenstein (2005). Consumer behavior studies can be found at DOE (2013b).
46. SEDC (2014).
47. See Giordano et al. (2013).
48. DOE (2014) “Smart Grid system report,” available at https://www.smartgrid.gov/files/2014-Smart-Grid-System-Report.pdf, accessed November 28, 2017.
49. EPRI (2011).
50. Joskow (2011).
51. See Gowrisankaran et al. (2016).
52. EPRI (2011) are the most comprehensive guidelines we are aware of, but investment in SG technologies are being accompanied by estimates, as the SGIG reports show.
53. DOE (2014).

54. MITEI (2011).
55. For a review of the role of technological change in green growth see Popp (2012).
56. QTR (2015).
57. Baker et al. (2013) provide a comprehensive review of cost benefit analysis for solar electricity in the short, medium and longer term.
58. QTR (2015). According to DOE (2017), the decrease in training programs in the electricity industry from the 1980s contributes to this workforce gap as the large number of baby boomers retire.
59. In whole or in part.
60. DOE (2017).
61. Ibid.
62. Although state commissions are in the early stages of this process and facing some strong opposition, as is exemplified by the recent decision of Nevada Assembly to restore retail net metering (Assembly Bill 405).
63. MIT Energy Initiative (2016).
64. http://pubs.naruc.org/pub/2E54C6FF-FEE9-5368-21AB-638C00554476.
65. DPS (2016).
66. QTR (2015).
67. Ibid.
68. DOE (2016b).
69. Figure 3.7 on p. 61 of the QTR, 2015 shows the phase-angle separation that occurred shortly before the 2003 blackout, and what the operators could have observed had the technology been in place at that time.
70. US–Canada Power System Outage Task Force (2014) “Final report on the August 14, 2003 blackout in the United States and Canada: Causes and recommendations,” April.
71. DOE (2016).
72. See more in DOE (2016b).
73. QTR (2015).
74. DOE (2015d).
75. QTR (2015).
76. DOE (2015d).
77. See DOE (2014).
78. QTR.
79. For more detail, see DOE (2016c).
80. EPRI (2011).
81. According to the QTR (2015) 70 percent of large power transformers and transmission lines are at least 25 years old and 60 percent of circuit breakers are at least 30 years old.
82. US Energy Information Administration (2016) “Electric power sales, revenue, and energy efficiency: Form EIA-861 detailed data files,” final yearly data (last release date October 6).
83. Automated feeder switches enables “self-healing” fault location, isolation and service restoration capabilities (FLISR).
84. QTR (2015); DOE (2013).
85. QTR (2015).
86. Borenstein (2012).
87. IEA (2016b).
88. US Federal Energy Regulatory Commission (2016) “Settlement intervals and shortage pricing in markets operated by regional transmission organizations and independent system operators,” available at https://www.ferc.gov/whats-new/comm-meet/2016/061616/E-2.pdf, accessed November 28, 2017.
89. See Ela et al. (2011a).
90. SEDC (2014).
91. For more on PJM Capacity Markets visit its webpage: http://learn.pjm.com/three-priorities/buying-and-selling-energy/capacity-markets.aspx, accessed on December 20, 2017.

92. Hogan (2005, 2013), Joskow (2008), Joskow and Tirole (2006, 2007).
93. This figure does not include the production of electricity by rooftop solar PV.
94. I. Penn and R. Menezes (2017) "Californians are paying billions for power they don't need," *LA Times*, February 5, available at http://www.latimes.com/projects/la-fi-electricity-capacity/, accessed November 28, 2017.
95. Borenstein, 2012.
96. Ibid.
97. Pete Wilson (California's former governor), Senator Don Nickles (former Oklahoma senator), Michele Bachmann (a former congresswoman) and Mitt Romney. See: https://www.theatlantic.com/business/archive/2017/01/regulations-jobs/513563/, accessed December 20, 2017.
98. See Berman and Bui (2001) and Greenstone (2002).
99. R. Schoof and D. Scott (2016) "Trump says plan to end climate spending would save $100B," Bloomberg BNA, November 2, available at http://www.bna.com/trump-says-plan-n57982082131/, accessed November 28, 2017.
100. The Tesla and SpaceX CEO announced he would leave the president's advisory boards following President's Trump withdrawal, and California, Washington and New York announced their intention to form an alliance to comply with the goals of the treaty, see G. Bade (2017) "Utilities post-Paris: Uncertainty rules power sector as Trump shatters climate consensus," Utility Dive, June 2, available at http://www.utilitydive.com/news/utilities-post-paris-uncertainty-rules-power-sector-as-trump-shatters-clim/444124/, accessed November 28, 2017.
101. EPA (2015).
102. Ohio, Minnesota, New Hampshire, Maryland and Illinois have recently joined New York, California and Texas, undertaking utility of the future proceedings.
103. Utilities tend to support demand charges for solar net metering customers, while solar industry groups are opposed to them.
104. Arizona Corporation Committee (2017) March 1, available at http://docket.images.azcc.gov/0000177680.pdf, accessed November 28, 2017.
105. DPS (2015b) Case 14-M-0101 "Proceeding on motion of the commission in regard to reforming the energy vision, order adopting regulatory policy framework and implementation plan" (issued February 26) (Track One Order).
106. Smart Grid Consumer Collaborative (SGCC) (2016) "Consumer driven technologies, 2016," available at http://smartenergycc.org/wp-content/uploads/2016/10/SGCC-Consumer-Driven-Technologies-Study-Executive-Summary-10-19-16.pdf, accessed November 28, 2017.
107. Regarding how the non-energy utility costs are paid, the low capacity value of solar and need for contracting for a backup and ramping costs magnified by solar PV penetration.
108. See Brown (2013) "Matching prices and value for distributed solar PV: SRP's proposal," available at http://www.srpnet.com/prices/priceprocess/pdfx/ABReport.pdf, accessed November 28, 2017.
109. Brown (2013) "Matching prices and value for distributed solar PV: SRP's proposal."
110. More on that in the VER section below.
111. M.L. Wald (2014) "How grid efficiency went south," *New York Times*, October 7, available at https://www.nytimes.com/2014/10/08/business/energy-environment/how-grid-efficiency-went-south-.html?_r=0, accessed November 28, 2017.
112. See https://www.ferc.gov/industries/electric/indus-act/demand-response/dem-res-adv-metering.asp, accessed on December 20, 2017.
113. IEA (2011).
114. Borenstein (2005).
115. Connecticut Light & Power's (CL&P's) Plan-it Wise Energy Pilot (PWEP), Pepco's PowerCentsDC Program (Pepco DC) and Baltimore Gas & Electric's Smart Energy Pricing Pilot (BGE, 2008).
116. The US FERC order 745 from March 2011 established that providers of economic

demand response that participate in wholesale power markets be compensated for demand reduction. A number of energy economists has opposed the order: according to HKS Professor Hogan order 745 overcompensates providers of demand response, resulting in a disuse of electricity when economic value exceeds the cost of producing. See Hogan (2010) for more.

117. See Sintov and Schultz (2015).
118. If very few engage, they may have to pay too high peak prices, since the total electricity demanded will still be too high in peak times.
119. See Banerjee and Duflo (2009) for randomized control trials.
120. See Allcott (2015) for site selection bias.
121. Study descriptions and evaluation can be found in DOE (n.d.) "Consumer behavior studies," available at https://www.smartgrid.gov/recovery_act/overview/consumer_behavior_studies.html, accessed November 28, 2017.
122. Reiss and White (2005) and Blonz (2016).
123. Gans et al. (2013), Faruqui et al. (2010b), Sexton (2015).
124. Further, Gilbert and Graff Zivin (2014).
125. I haven't been able to find published papers on the impact of peak pricing in the commercial and industrial sector.
126. He compares establishments that just missed the eligibility criteria.
127. See Smith (2010).
128. Sintov and Schultz (2015), Christensen et al. (2015), Allcott (2011).
129. C. Wolfram (2013) "Smart meters but dumb pricing? Not in Sacramento," Berkeley Blog, November 21, available at http://blogs.berkeley.edu/2013/11/21/smart-meters-but-dumb-pricing-not-in-sacramento/, accessed November 28, 2017.
130. See Fowlie et al. (2017).
131. See Burger and Luke (2016).
132. Allcott and Rogers (2014).
133. In this paper, the experiment comprised 600,000 households.
134. Sintov and Schultz (2015).
135. See Cialdini et al. (1991) for more on descriptive and injunctive norms.
136. See also Ito et al. (2015).
137. See Benabou and Tirole (2003) for more on extrinsic and intrinsic motivations.
138. US FERC order 745 from March 2011 established that providers of economic demand response that participate in wholesale power markets be compensated for demand reduction.
139. FERC requires balancing authorities to constantly match supply and demand within their respective balancing areas.
140. National Renewable Energy Laboratory (NREL) (2016).
141. CAISO (2016).
142. C.W. Draffin, Jr. (2016) "Cybersecurity, white paper," MIT Energy Initiative Utility of the Future, December 15, available at https://energy.mit.edu/wp-content/uploads/2016/12/CybersecurityWhitePaper_MITUtilityofFuture_-2016-12-05_Draffin.pdf, accessed November 28, 2017.
143. The North American Electric Reliability Corporation (NERC) has developed cybersecurity regulations at the bulk power and transmission levels (NERC, 2016), however they are still lacking at the distribution level. The first European legislation on cybersecurity, the Network and Information Security (NIS) Directive, is also very recent (2016).
144. DOE (2017).
145. The increased concern has been related to the Ukrainian cyberattack: H.K. Trabish (2017) "Why utilities say grid security is the most pressing sector issue of 2017," Utility Dive, available at http://www.utilitydive.com/news/why-utilities-say-grid-security-is-the-most-pressing-sector-issue-of-2017/440056/, accessed November 28, 2017.
146. Idaho National Laboratory (INL) (2016).
147. J. Condliffe (2016) "Ukraine's power grid gets hacked again, a worrying sign for

infrastructure attacks," *Technology Review*, December 21, available at https://www.technologyreview.com/s/603262/ukraines-power-grid-gets-hacked-again-a-worrying-sign-for-infrastructure-attacks/, accessed November 28, 2017.

148. Lloyd's (2015) "Emerging risk report 2015," Centre for Risk Studies: University of Cambridge, Judge Business School.
149. C.W. Draffin, Jr. (2016) "Cybersecurity, white paper."

REFERENCES

ACEEE (2016) "Energy usage data access: A getting-started guide for regulators," available at http://aceee.org/sector/state-policy/toolkit/data-access, accessed November 28, 2017.

Allcott, Hunt. (2011) "Social norms and energy conservation," *Journal of Public Economics*, **95**, pp. 1082–95.

Allcott, Hunt. (2015) "Site Selection Bias in Program Evaluation," *Quarterly Journal of Economics*, **130** (3), pp. 1117–65.

Allcott, Hunt, and Rogers, Todd. (2014) "The Short-Run and Long-Run Effects of Behavioral Interventions: Experimental Evidence from Energy Conservation," *American Economic Review*, **104**, (10) (October), pp. 3003–37.

Arizona Corporation Committee (2017) March 1, available at http://docket.images.azcc.gov/0000177680.pdf, accessed November 28, 2017.

Ayres, Ian, Raseman, Sophie and Shih, Alice. (2013) "Evidence from two large field experiments that peer comparison feedback can reduce residential energy usage", *The Journal of Law, Economics, and Organization*, **29** (5), pp. 992–1022.

Bade, G. (2017) "Utilities post-Paris: Uncertainty rules power sector as Trump shatters climate consensus," *Utility Dive*, June 2, available at http://www.utilitydive.com/news/utilities-post-paris-uncertainty-rules-power-sector-as-trump-shatters-clim/444124/, accessed November 28, 2017.

Banerjee, Abhijit V. and Duflo, Esther (2009) "The Experimental Approach to Development Economics," *Annual Review of Economics*, Vol. 1, pp. 151–78.

Baker, Erin, Fowlie, Meredith, Lemoine, Derek and Reynolds, Stanley S. (2013) "The Economics of Solar Electricity," *Annual Review of Resource Economics*, **5**, pp. 387–426.

Benabou, Roland, and Jean Tirole. (2003) "Intrinsic and Extrinsic Motivation," *Review of Economic Studies*, **70** (3), pp. 489–520.

Berman, Eli and Bui, Linda T.M. (2001) "Environmental regulation and productivity: Evidence from oil refineries," *Review of Economics and Statistics*, **83** (3), pp. 498–510.

Blonz Joshua A. (2016) "Making the Best of the Second-Best: Welfare Consequences of Time-Varying Electricity Prices," November 2016, EI HAAS WP 275.

Bollinger, Bryan and Gillingham, Kenneth. (2012) "Peer effects in the diffusion of solar photovoltaic panels," *Marketing Science*, **31**, pp; 900–912.

Bollinger, Bryan and Wesley Hartmann (2015). "Welfare Effects of Home Automation Technology with Dynamic Pricing," Working Paper.

Borenstein, Severin. (2005) "The Long-Run Efficiency of Real-Time Electricity Pricing: Bill Volatility and Hedgability," *Energy Journal*, **28** (2), pp. 111–30.

Borenstein, Severin (2007) "Wealth Transfers Among Large Customers from Implementing Real-Time Retail Electricity Pricing," *The Energy Journal*, **28** (2).

Borenstein, Severin (2012) "The Private and Public Economics of Renewable Electricity Generation", *Journal of Economic Perspectives*, **26** (1).

Borenstein, Severin. and Holland, Stephen (2005) "On the Efficiency of Competitive Electricity Markets With Time-Invariant Retail Prices," *Rand Journal of Economics*, Vol. 36.

Borenstein, Severin, Jaske, Michael, and Rosenfeld, Arthur (2002) "Dynamic Pricing, Advanced Metering, and Demand Response in Electricity Markets," University of

California Energy Institute, Paper CSEM WP 105, 2002, available at https://ei.haas.berkeley.edu/research/papers/CSEM/semwp105.pdf.

Bower, Joseph L., and Christensen, Clayton M. (1995) "Disruptive Technologies: Catching the Wave," *Harvard Business Review*, January–February.

Brown, A. (2013) "Matching prices and value for distributed solar PV: SRP's proposal," available at http://www.srpnet.com/prices/priceprocess/pdfx/ABReport.pdf, accessed November 28, 2017.

Brown, Ashley, and Bunyan, Jillian (2014) "Valuation of Distributed Solar: A Qualitative View," *The Electricity Journal*, **27**(10).

Burger, Scott P., and Luke, Mark (2016) "Business Models for Distributed Energy Resources: A Review and Empirical Analysis", MIT Energy Initiative WP-2016-02, available at https://energy.mit.edu/wp-content/uploads/2016/04/MITEI-WP-2016-02.pdf, accessed November 27, 2017.

California Independent System Operator (CAISO) (2016) "Quantifying EIM benefits: 2016 Q2 report," Folsom, CA: CAISO, July 8, available at https://www.caiso.com/Documents/ISO-EIMBenefitsReportQ2_2016.pdf, accessed November 28, 2017.

Campbell, R.J. (2012) "Weather-Related Power Outages and Electric System Resiliency," Congressional Research Service, August 28, available at http://woodpoles.org/portals/2/documents/CRS_Outages.pdf, accessed on November 27, 2017.

Christensen, Clayton (1997) "The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail," *Harvard Business Review Press*.

Christensen, Clayton M., Raynor, Michael E. and McDonald, Roy (2015) "What Is Disruptive Innovation?," *Harvard Business Review*, December 2015.

Cialdini, R.B., Kallgren, C.A., and Reno, R.R. (1991) "A focus theory of normative conduct," *Advances in Experimental Social Psychology*, Vol. 24, pp. 201–34.

Condliffe, J. (2016) "Ukraine's power grid gets hacked again, a worrying sign for infrastructure attacks," *Technology Review*, December 21, available at https://www.technologyreview.com/s/603262/ukraines-power-grid-gets-hacked-again-a-worrying-sign-for-infrastructure-attacks/, accessed November 28, 2017.

Cramton, P., Ockenfels, A. and Stoft, S. (2013) "Capacity Market Fundamentals", *Economics of Energy & Environmental Policy*, 2.

Cramton, P. and Stoft, S. (2006) "The Convergence of Market Designs for Adequate Generating Capacity with Special Attention to the CAISO's Resource Adequacy Problem: A White Paper for the Electricity Oversight Board," available at http://www.cramton.umd.edu/papers2005-2009/cramton-stoft-market-design-for-resource-adequacy.pdf, accessed on November 27, 2017.

De Castro, L., and Dutra, J. (2013) "Paying for the Smart Grid," *Energy Economics*, Vol. 40, S74–S84.

DOE (n.d.) "The Smart Grid: an introduction," available at https://www.energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_SG_Book_Single_Pages%281%29.pdf, accessed November 28, 2017.

DOE (2007) US Department of Energy "Consumer behavior studies," available at https://www.smartgrid.gov/recovery_act/overview/consumer_behavior_studies.html, accessed November 28, 2017.

DOE (2012a) US Department of Energy. "The Smart Grid: An Introduction. How a smarter grid works as an enabling engine for our economy, our environment and our future," available at https://energy.gov/sites/prod/files/oeprod/DocumentsandMedia/DOE_SG_Book_Single_Pages%281%29.pdf, accessed on December 20, 2017.

DOE (2012b) U.S. Department of Energy, "Smart grid investment grant program: progress report," available at https://energy.gov/sites/prod/files/Smart%20Grid%20Investment%20Grant%20Program%20-%20Progress%20Report%20July%202012.pdf, accessed on December 20, 2017.

DOE (2013a) "Demand response defers investment in new power plants in Oklahoma," April, available at https://www.smartgrid.gov/sites/default/files/doc/files/OGE%20CBS%20case%20study.pdf, accessed November 28, 2017.

DOE (2013b) "Voices of experience," available at https://www.smartgrid.gov/files/VoicesofExperience_Brochure_9.26.2013.pdf, accessed November 28, 2017.

DOE (2014) "Smart Grid system report," available at https://www.smartgrid.gov/files/2014-Smart-Grid-System-Report.pdf, accessed November 28, 2017.

DOE (2015a) "U.S. Department of Energy Quadrennial Technology Review," 2015, available at https://energy.gov/sites/prod/files/2015/09/f26/Quadrennial-Technology-Review-2015_0.pdf, accessed on November 27, 2017.

DOE (2015b) "U.S. Department of Energy, Quadrennial Energy Review: Energy Transmission, Storage, and Distribution Infrastructure,", April 2015, available at https://energy.gov/epsa/downloads/quadrennial-energy-review-first-installment, accessed November 28, 2017.

DOE (2015c) "US Department of Energy, Grid Modernization Multi-Year Program Plan," November 2015, available at https://energy.gov/sites/prod/files/2016/01/f28/Grid%20Modernization%20Multi-Year%20Program%20Plan.pdf, accessed on December 20, 2017.

DOE (2015d) "Opportunities for Energy Efficiency Improvements in the U.S. Electricity Transmission and Distribution System", available at https://energy.gov/sites/prod/files/2015/04/f22/QER%20Analysis%20-%20Opportunities%20for%20Energy%20Efficiency%20Improvements%20in%20the%20US%20Electricity%20Transmission%20and%20Distribution%20System_0.pdf, accessed on December 20, 2017.

DOE (2016a) "Smart Grid Investment Grant Program Final Report", available at https://www.smartgrid.gov/files/Final_SGIG_Report_20161220.pdf, accessed on December 20, 2017.

DOE (2016b) "Advancement of Synchrophasor Technology in Projects Funded by the ARRA," available at https://www.smartgrid.gov/files/20160320_Synchrophasor_Report.pdf, accessed on December 20, 2017.

DOE (2016c) "Distribution Automation: Final Report from the SGIG Program," available at https://energy.gov/sites/prod/files/2016/11/f34/Distribution%20Automation%20Summary%20Report_09-29-16.pdf, accessed on December 20, 2017.

DOE (2017) "U.S. Department of Energy, Quadrennial Energy Review: Transforming the Nation's Electricity System," January 2017, available at https://energy.gov/epsa/downloads/quadrennial-energy-review-second-installment, accessed November 28, 2017.

DPS (2015a) CASE 14-M-0101 "Proceeding on motion of the commission in regard to reforming the energy vision: Order establishing the benefit cost analysis framework," May 29, http://www3.dps.ny.gov/W/PSCWeb.nsf/All/C12C0A18F55877E785257E6F005D533E?OpenDocument, accessed November 28, 2017.

DPS (2015b) Case 14-M-0101 "Proceeding on motion of the commission in regard to reforming the energy vision, order adopting regulatory policy framework and implementation plan" (issued February 26) (Track One Order).

DPS (2016) "Key documents," available at http://www3.dps.ny.gov/W/PSCWeb.nsf/All/C12C0A18F55877E785257E6F005D533E?OpenDocument, accessed November 28, 2017.

Draffin, Jr., C.W. (2016) "Cybersecurity, white paper," MIT Energy Initiative Utility of the Future, December 15, available at https://energy.mit.edu/wp-content/uploads/2016/12/CybersecurityWhitePaper_MITUtilityofFuture_-2016-12-05_Draffin.pdf, accessed November 28, 2017.

Ela, E. and B. Kirby (2008) "ERCOT event on February 26, 2008: Lessons learned," National Renewable Energy Laboratory, July.

Ela, Erik, Kirby, Brendan, Navid, Nivad and Smith, J. Charles (2011a) "Effective Ancillary Services Market Designs on High Wind Power Penetration Systems" Conference Paper NREL/CP-5500-53514, available at https://www.nrel.gov/docs/fy12osti/53514.pdf, accessed on December 20, 2017.

Ela, Erik, Milligan, Michael and Kirby, Brendan (2011b) "Operating Reserves and Variable Generation: A comprehensive review of current strategies, studies, and fundamental research on the impact that increased penetration of variable renewable generation has on power system operating reserves," National Renewable Energy Laboratory, WE110920.

EPA (2015) U.S. Environmental and Protection Agency. "Energy and Environment Guide to Action State Policies and Best Practices for Advancing Energy Efficiency, Renewable Energy, and Combined Heat and Power," available at https://www.epa.gov/sites/production/files/2015-08/documents/guide_action_full.pdf, accessed on December 20, 2017.

EPRI (2011) "Estimating the Costs and Benefits of the Smart Grid: A Preliminary Estimate of the Investment Requirements and the Resultant Benefits of a Full Functioning Smart Grid," Technical Report, 2011.

Eureletric (2014) "Flexibility and Aggregation: Requirements for their interaction in the market," January 2014, available at http://www.eurelectric.org/media/115877/tf_bal-agr_report_final_je_as-2014-030-0026-01-e.pdf, accessed on November 27, 2017.

European Union (2016a) "Directive (EU) 2016/1148: Concerning measures for a high common level of security of networks and information systems across the Union," July 6, Brussels, Belgium: European Union.

European Union (2016b) "Regulation (EO) 2016/679: on the protection of natural persons with regard to the processing of personal data and on the free movement of such data, and repealing Directive 95/46/EC (General Data Protection Regulation)," April 27, Brussels, Belgium: European Union.

Faruqui, A., and Palmer, J. (2011) "Dynamic Pricing and Its Discontents," *Regulation*, **34** (3), pp. 16–22.

Faruqui, Ahmad and Sergici, Sanem. (2009) "Household response to dynamic pricing of electricity: a survey of 15 experiments," *Journal of Regulatory Economics*, **38** (2), pp. 193–225.

Faruqui, A., Sergici, S., and Palmer, J. (2010a) "The Impact of Dynamic Pricing on Low Income Customers," IEE Whitepaper.

Faruqui, Ahmad, Sergici, Sanem and Sharif, Ahmed. (2010b) "The impact of informational feedback on energy consumption—A survey of the experimental evidence," *Energy*, **35** (4), pp. 1598–1608.

Federal Energy Regulatory Commission (FERC) (2016) "Assessment of DR and AM, Staff report, FERC for state legislative and regulatory activity for AMI deployment," available at https://www.ferc.gov/legal/staff-reports/2016/DR-AM-Report2016.pdf, accessed on November 27, 2017.

Fowlie, M., Catherine Wolfram, C. Anna Spurlock, Annika Todd, Patrick Baylis, and Peter Cappers. (2017) "Default Effects and Follow-On Behavior: Evidence from an Electricity Pricing Program," EI @ Haas WP 280, June.

Gans, Will, Alberini, Anna and Longo, Alberto (2013) "Smart meter devices and the effect of feedback on residential electricity consumption: Evidence from a natural experiment in Northern Ireland," *Energy Economics*, **36**, pp. 729–43.

GAO (2011) "US Government Accountability Office Electricity Grid Modernization: Progress Being Made on Cybersecurity Guidelines, but Key Challenges Remain to Be Addressed," Washington, D.C., GAO-11-117, January 2011, available at https://www.gao.gov/assets/320/314410.pdf, accessed on December 20, 2017.

Gilbert, Ben, and Graff Zivin, Joshua. (2014) "Dynamic salience with intermittent billing: Evidence from smart electricity meters," *Journal of Economic Behavior & Organization*, **107**, pp. 176–90.

Giordano, V., A. Meletiou, C.-F. Covrig, A.M. Mengolini, M. Ardelean, G. Fulli, M. Sánchez Jiménez and C. Filiou (2013) "Smart grid projects in Europe: Lessons learned and current developments—2012 update," Luxembourg: Publications Office of the European Union, available at http://publications.jrc.ec.europa.eu/repository/handle/111111111/28191, accessed October 24, 2014.

Gowrisankaran, G., Reynolds, Samano, M. (2016) "Intermittency and the Value of Renewable Energy," *Journal of Political Economy*, **124** (4), 1187–1234.

Graziano, Marcello and Gillingham, Kenneth. (2014) "Spatial patterns of solar photovoltaic system adoption: the influence of neighbors and the built environment," *Journal of Economic Geography*, **15** (4), pp. 815–39.

Greenstone, Michael, (2002) "The Impacts of Environmental Regulations on Industrial Activity: Evidence from the 1970 and 1977 Clean Air Act Amendments and the Census of Manufactures," *Journal of Political Economy*, **110** (6), pp. 1175–1219.

Gribik, P.R, Hogan, W., and Susan L. Popeii (2007) "Market-Clearing Electricity Prices and Energy Uplift," available at http://www.lmpmarketdesign.com/papers/Gribik_Hogan_Pope_Price_Uplift_123107.pdf, accessed on November 27, 2017.

Guthrie, G. (2006) "Regulating infrastructure: the impact on risk and investment," *Journal of Economic Literature*, **44** (4) December, pp. 925–72.

Hledik, Ryan and Greenstein, Gus (2016) "The distributional impacts of residential demand charges," *The Electricity Journal*, **29** (6), 33–41.

Hogan, William W. (2005) "On an 'Energy Only Electricity Market Design for Resource Adequacy'," available at https://sites.hks.harvard.edu/fs/whogan/Hogan_Energy_Only_092305.pdf, accessed on December 20, 2017.

Hogan, W. (2010) "Implications for Consumers of the NOPR's Proposal to Pay the LMP for All Demand Response," Prepared for the Electric Power Supply Association, comments on FERC Docket No. RM10-17-000, May.

Hogan, William (2013) "Electricity Scarcity Pricing Through Operating Reserves," *Economics of Energy & Environmental Policy*, **2** (2), 65–86.

Holttinen, H., Meibom, P., Ensslin, C., Hofmann, L., Mccann, J. and Pierik, J. (2013) "Design and operation of power systems with large amounts of wind power," IEA WIND task, VTT Research Notes 2493, available at http://www.vtt.fi/inf/pdf/technology/2012/T75.pdf, accessed on November 27, 2017.

Hölzle, U. (2016) "We're set to reach 100% renewable energy — and it's just the beginning," Google Blog, December 6, available at https://blog.google/topics/environment/100-percent-renewable-energy/, accessed November 28, 2017.

IPCC (2014) "Climate change 2014 synthesis report," available at http://www.ipcc.ch/report/ar5/syr/, accessed November 28, 2017.

IEA (2016a) "World Energy Outlook".

Idaho National Laboratory. "Cyber Threat and Vulnerability Analysis of the U.S. Electric Sector", 2016, available at https://info.publicintelligence.net/INL-CyberThreatsElectricSector.pdf, accessed November 27, 2017.

IEA (2016b) "Repowering Markets: Market design and regulation during the transition to low-carbon power systems," available at https://www.iea.org/publications/freepublications/publication/REPOWERINGMARKETS.pdf, accessed November 27, 2017.

Ito, Koichiro, Ida, Takanori, and Tanaka, Makoto (2015) "The persistence of moral suasion and economic incentives: Field experimental evidence from energy demand," National Bureau of Economic Research, Working Paper No. 20910, January.

Jessoe, Katrina and Rapson, David (2014) "Knowledge is (Less) Power: Experimental Evidence from Residential Energy Use," *American Economic Review*, **104** (4), April, pp. 1417–38.

Joskow, P.L. (2008) "Capacity payments in imperfect electricity markets: Need and design," *Utilities Policy*, **16** (3), pp. 159–70.

Joskow, P. (2011) "Creating a Smarter U.S. Electricity Grid", Discussion paper, available at https://economics.mit.edu/files/7427, accessed on November 27, 2017.

Joskow, P., and Tirole, J. (2006) "Retail Electricy Competition," *Rand Journal of Economics*, **37** (4), pp. 799–815, 2006.

Joskow, P., and Tirole, J. (2007) "Reliability and Competitive Electricity Markets," *Rand Journal of Economics*, **38**(1), pp. 60–84, 2007.

Joskow, Paul L. and Wolfram, Catherine D. (2012) "Dynamic Pricing of Electricity," *American Economic Review* Papers and Proceedings, **102** (3), pp. 381–85.

Kelly-Detwiler, Peter (2015) "Mind the Gap: Energy Availability and the Disconnect with Data" (Houston, TX: Northbridge Energy Partners, LLC, 2015), 3, https://campaigns.verneglobal.com/mind-the-gap.

Kind, Peter (2013) "Disruptive Challenges: Financial Implications and Strategic Responses to a Changing Retail Electric Business", paper prepared for the Edison Electric Institute, January.

Leijten, Fenna R. M., Bolderdijk J. Willem, Keizer, Kees, Gorira, Madelijne, Van der Werff, Ellen, and Steg, Linda (2014) "Factors that influence consumers' acceptance of future energy systems: the effects of adjustment type, production level, and price," *Energy Efficiency*, **7** (6), pp. 973–85.

Lloyd's (2015) "Emerging risk report 2015," Centre for Risk Studies: University of Cambridge, Judge Business School.

McClelland, Lou and Cook, Stuart W. (1980) "Promoting Energy Conservation in Master-metered Apartments through Group Financial Incentives," *Journal of Applied Social Psychology*, **10**, pp. 20–31.

MIT Energy Initiative (2016) "Utility of the Future: an MIT Energy Initiative response to an industry in transition,"available athttps://energy.mit.edu/wp-content/uploads/2016/12/Utility-of-the-Future-Full-Report.pdf, accessed on December, 20, 2017.

MITEI (2011) "The future of the electric grid," available at http://energy.mit.edu/research/future-electric-grid/, accessed November 28, 2017.

North American Electric Reliability Council (NERC) (2009) "Accommodating High Levels of Variable Generation," Special Report, available at http://www.nerc.com/files/ivgtf_report_041609.pdf, accessed on December 20, 2017.

NERC (2016) "Critical infrastructure protection standards," Washington, D.C.: North American Electric Reliability Corporation.

National Energy Technology Laboratory (NETL) (2009) "A Compendium of Smart Grid technologies," available at https://www.smartgrid.gov/files/a_compendium_of_smart_grid_technologies_06-2009.pdf, accessed on November 28, 2017.

National Renewable Energy Laboratory (NERL) (2015) "Overgeneration from Solar Energy in California: A Field Guide to the Duck Chart," prepared by Denholm, Matthew O'Connell, Gregory Brinkman, and Jennie Jorgenson, Technical Report NREL/TP-6A20-65023, 2015.

NREL (2016) "Big, fast and flexible: Grid operation for efficient variable renewable integration," webinar presented on October 11, available at https://cleanenergysolutions.org/training/flexible-grid-operations-variable-renewable-integration, accessed November 28, 2017.

Nemet, G. F. (2006) "Beyond the learning curve: factors influencing cost reductions in photovoltaics," *Energy Policy* **34**, pp. 3218–32.

New York Public Service Commission (2017), Cases 15-E-0751 and 15-E-0082: "Order on Net Energy Metering Transition, phase one of value of distributed energy resources, and related matters", March 9, 2017.

Office of Electricity Delivery & Energy Reliability (n.d.) "Grid modernization and the smart grid," available at http://energy.gov/oe/services/technology-development/smart-grid, accessed November 28, 2017.

Penn, I. and R. Menezes (2017) "Californians are paying billions for power they don't need," *LA Times*, February 5, available at http://www.latimes.com/projects/la-fi-electricity-capacity/, accessed November 28, 2017.

Pérez-Arriaga, Ignacio J. (2011) "Managing large scale penetration of intermittent renewables" 2011 MITEI SYMPOSIUM, available at https://www.iit.comillas.edu/docs/IIT-11-181A.pdf, accessed on November 27, 2017.

Pérez-Arriaga, Ignacio J., Burgerb, Scott and Gómezc, Tomás (2016) "Electricity Services in a More Distributed Energy Future," Center for Energy & Environmental Policy Research, MIT, CEEPR WP 2016-005, 2016, available at http://energy.mit.edu/wp-content/uploads/2016/08/CEEPR-WP-2016-005.pdf.

Popp, D. (2002) "Induced Innovation and Energy Prices," *American Economic Review*, **92** (1), pp. 160–80.

Popp, D. (2012) "The role of technological change in green growth," Working Paper 18506, NBER.

Reiss, Peter C. and Matthew W. White (2005) "Household Electricity Demand, Revisited," *The Review of Economic Studies*, **72** (3), pp. 853–83.

Richter, Mario (2013) "German utilities and distributed PV: How to overcome barriers to business model innovation," *Renewable Energy*, **55**, pp 456–66.

Schoof, R. and D. Scott (2016) "Trump says plan to end climate spending would save $100B," Bloomberg BNA, November 2, available at http://www.bna.com/trump-says-plan-n57982082131/, accessed November 28, 2017.

Schultz, Wesley, Nolan, Jessica, Cialdini, Robert, Goldstein, Noah, and Griskevicius, Vladas (2007) "The Constructive, Destructive, and Reconstructive Power of Social Norms," *Psychological Science*, **18**, pp. 429–34.

Sexton, Steven (2015) "Automatic Bill Payment and Salience Effects: Evidence from Electricity Consumption," *Review of Economics and Statistics*, **97** (2), pp. 229–41.

Sintov, Nicole D. and Schultz, P. Wesley (2015) "Unlocking the potential of smart grid technologies with behavioral science," *Frontiers in Psychology*, 1–8.

Smart Energy Demand Coalition (SEDC) (2014) "Mapping Demand Response in Europe Today," available at http://www.smarten.eu/wp-content/uploads/2015/09/Mapping-Demand-Response-in-Europe-Today-2015.pdf, accessed on November 27, 2017.

Smart Grid Consumer Collaborative (SGCC) (2016) "Consumer driven technologies, 2016," available at http://smartenergycc.org/wp-content/uploads/2016/10/SGCC-Consumer-Driven-Technologies-Study-Executive-Summary-10-19-16.pdf, accessed November 28, 2017.

Smith, Rebecca. "What Utilities Have Learned From Smart-Meter Tests. . .," *Wall Street Journal*, February 22, 2010, available at https://www.wsj.com/articles/SB10001424052748704878904575031020562238094, accessed on November 28, 2017.

Taneja, Jay (2017) "Measuring Electricity Reliability in Kenya," Working paper, available at http://blogs.umass.edu/jtaneja/files/2017/05/outages.pdf, accessed on November 27, 2017.

Trabish, H.K. (2017) "Why utilities say grid security is the most pressing sector issue of 2017," *Utility Dive*, available at http://www.utilitydive.com/news/why-utilities-say-grid-security-is-the-most-pressing-sector-issue-of-2017/440056/, accessed November 28, 2017.

US Congress (2009), Public Law 111 – 5 – American Recovery and Reinvestment Act of 2009, available at https://www.gpo.gov/fdsys/pkg/PLAW-111publ5/pdf/PLAW-111publ5.pdf, accessed December 20, 2017.