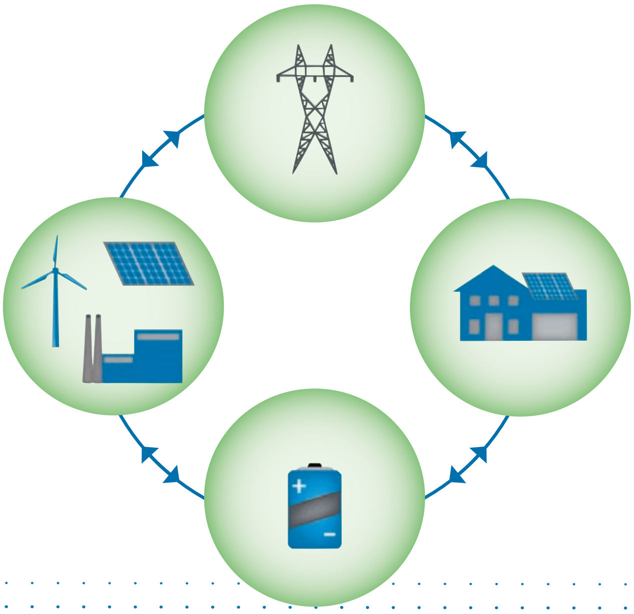
IRENA
International Renewable Energy Agency

Working Paper

SMART GRIDS AND RENEWABLES

A Guide for Effective Deployment



November 2013

About IRENA

The International Renewable Energy Agency (IRENA) is an intergovernmental organisation that supports countries in their transition to a sustainable energy future, and serves as the principal platform for international cooperation, a centre of excellence, and a repository of policy, technology, resource and financial knowledge on renewable energy. IRENA promotes the widespread adoption and sustainable use of all forms of renewable energy, including bioenergy, geothermal, hydropower, ocean, solar and wind energy in the pursuit of sustainable development, energy access, energy security and low-carbon economic growth and prosperity.
www.irena.org

Acknowledgements

The work for the preparation of this paper was led by Paul Komor and Anderson Hoke, University of Colorado, Boulder, Colorado, USA. The paper benefitted from very valuable comments from Rainer Bacher (Bacher Energie, Switzerland), Melissa Chan (Navigant Consulting, USA), Kazuyuki Takada (New Energy and Industrial Technology Development Organization, Japan), Matt Wakefield (EPRI, USA).

Authors: Ruud Kempener (IRENA), Paul Komor and Anderson Hoke (University of Colorado)

For further information or to provide feedback, please contact: Ruud Kempener, IRENA Innovation and Technology Centre. E-mail: RKempener@irena.org or secretariat@irena.org.

Disclaimer

SMART GRIDS
AND
RENEWABLES

A Guide for
Effective Deployment

November 2013

TABLE OF CONTENTS

Executive Summary

Electricity generation from renewable sources will need to increase significantly to achieve the Sustainable Energy for All (SE4ALL) objective of doubling the share of renewable energy (RE) in the global energy mix by 2030. Fortunately, there is growing evidence in many countries that high levels of renewable energy penetration in the grid are technically and economically feasible, particularly as solar and wind technologies increasingly reach grid parity in economic terms.

However, continuous and expanded growth of the share of renewables in centralised and decentralised grids requires an effective new approach to grid management, making full use of "smart grids" and "smart grid technologies". Existing grid systems already incorporate elements of smart functionality, but this is mostly used to balance supply and demand. Smart grids incorporate information and communications technology into every aspect of electricity generation, delivery and consumption in order to minimise environmental impact, enhance markets, improve reliability and service, and reduce costs and improve efficiency (EPRI 2013).

These technologies can be implemented at every level, from generation technologies to consumer appliances. As a result, smart grids can play a crucial role in the transition to a sustainable energy future in several ways: facilitating smooth integration of high shares of variable renewables; supporting the decentralised production of power; creating new business models through enhanced information flows, consumer engagement and improved system control; and providing flexibility on the demand side.

This report is intended as a pragmatic user's guide on how to make optimal use of smart grid technologies for the integration of renewables into the grid. It outlines the systemic approach that is required to address both the technical and non-technical issues associated with the implementation of smart grids for renewables. These issues are:

- the importance of demonstration projects;
- evaluation of specific technology requirements for different penetration levels;
- the development of a business case beyond costs;
- leverage of private sector investments;
- consideration of the role of innovation and continual technological change;
- the need to recognise and respond to inertia within the electricity sector; and
- the importance of regulation associated with data ownership, grid security issues, standards, and the role of new private sector grid players.

The report also provides a detailed review of smart grid technologies for renewables, including their costs, technical status, applicability and market maturity for various uses. Smart grid technologies are divided roughly into three groups:

- *Well-established:* Some smart grid components, notably distribution automation and demand response, are well-established technologies that directly enable renewables and are usually cost-effective, even without taking into consideration the undeniable benefits of sustainability related to renewable energy integration.
- *Advanced:* Smart inverters and renewable forecasting technologies are already used to increase the efficiency and productivity of renewable power generation, yet tend to entail additional costs. These devices start to help noticeably when capacity penetration for renewables reaches 15% or more (on any section of the grid) and become essential as this capacity penetration approaches 30%, although there is little downside to choosing smart inverters even at low penetration levels.
- *Emerging:* Distributed storage and micro-grids are generally not "entry level" smart grid technologies and thus are less well developed. Most utilities should focus on other technologies first, except in special circumstances (such as with grant funding, high reliability requirements, or remote locations).

This overview shows that a range of enhanced smart grid technologies is already available to improve grid performance and enable higher penetration levels of renewable energy. Furthermore, the use of smart grids is cost effective when installing new grids or upgrading old ones. Examples of cost-effective smart grid technologies include "smart meters", which can measure and track the output of a rooftop photovoltaic (PV) system and send that data back to the utility operating the grid, and "smart transformers" that will automatically notify grid operators and technicians if the transformer's internal temperature exceeds normal limits.

Applications of smart grid technologies can be found across the world, from isolated islands to very large integrated systems. For developed countries, smart grid technologies can be used to upgrade, modernise or extend old grid systems, while at the same time providing opportunities for new, innovative solutions to be implemented. For developing and emerging countries, smart grid technologies are essential to avoid lock-in of outdated energy infrastructure, attract new investment streams, and create efficient and flexible grid systems that will be able to accommodate rising electricity demand and a range of different power sources.

Smart grid technologies are already making significant contributions to electricity grid operation in several countries. Case studies from Denmark, Jamaica, the Netherlands, Singapore, and the United States (New Mexico and Puerto Rico) are featured in this report to highlight successful combinations of smart grid technologies with renewable energy integration. Yet, as these case studies also show, the successful implementation of smart grid technologies for renewables requires changes in policy and regulatory frameworks to address non-technical issues, particularly with regards to the distribution of benefits and costs across suppliers, consumers and grid operators.

With renewable power shares sure to continue increasing, smart grid technologies in combination with appropriate supporting policies and regulations will be essential to transform the electricity system and create the grid infrastructure to support a sustainable energy future. This report is a first step in providing guidance on smart grids and renewables for a range of situations—from small islands to large intercontinental grid projects—and outlining the actions required for this ambitious energy transformation to happen.

1. Introduction: Smart Grids and Renewables

In 2012, in the context of the "International Year for Sustainable Energy for All" (SE4ALL), the International Renewable Energy Agency (IRENA) launched a global renewable energy roadmap for doubling the share of renewables in the global energy mix by 2030. The aspirational target of this roadmap—called REMAP 2030—is derived from the SE4ALL initiative, which is currently chaired by the United Nations Secretary-General and the World Bank President.

The initial results of REMAP 2030 concluded that the share of renewables in the electricity sector will have to double from 20% today to at least 40% to achieve this aspirational target. This means that in many countries the renewable share of electricity generation has to increase substantially. For developed countries, transforming the electricity sector to absorb more renewables requires upgrades and modernised extensions of old grid systems, while also opening opportunities for introduce new, innovative solutions. For emerging or to developing countries, the priorities are to avoid lock-in with conventional energy sources, to attract new streams of investment, and to accommodate a range or energy sources to meet rising electricity demand.

Fortunately, there is growing evidence in many countries that high levels of renewables are technically and economically feasible. This report provides six case studies, from Denmark, Jamaica, the Netherlands, Singapore and the United States (New Mexico and Puerto Rico), to illustrate how smart grid technologies are enabling higher shares of renewable energy.

These case studies show that a transformation of the electricity sector towards renewables is already happening, but several studies suggest that even higher shares of renewable energy power generation are foreseen. For example:

- The International Energy Agency's (IEA) "sustainable future" scenario shows renewables providing 57% of world electricity by 2050 (IEA, 2012, p. 10).
- A comprehensive analysis of the United States (U.S.) electricity system by the U.S. Department of Energy concluded that "Renewable electricity generation from technologies that are commercially available today… [could] supply 80% of total U.S. electricity generation in 2050" (Hand, *et al.*, 2012, p. iii).
- A low-carbon scenario for Europe found that 50% renewable electricity by 2030 is achievable at a cost comparable to that of the business-as-

Case Study 1: Denmark's seamless wind integration

Denmark has long used several smart grid technologies to support the world's highest wind penetration. With around 30% of its electricity coming from wind, the country claims the highest electric system reliability in Europe. Crucially, wind energy forecasting is integrated into the daily grid operations of Denmark and surrounding countries. High Voltage Direct Current (HVDC) ties link Denmark's two separate electric grids, while both Alternating Current (AC) and HVDC ties link Denmark to neighbouring countries, allowing wind power that is abundant in one area to be shared with others. Other smart grid technologies used to manage Denmark's wind power include smart charging of electric vehicles (EVs) and demand-response (DR) control of heating loads.

Denmark's largest utility, Energinet.dk, is testing a system that uses advanced distribution automation (DA) to divide the grid into autonomous cells, or "virtual power plants" (VPPs), consisting of smart wind inverters and distributed generation, such as combined heat and power plants. Some of these cells can operate in isolation as "islanded" micro-grids.

Denmark plans to increase wind energy penetration to 50% by 2025. A study compared the cost of using smart grid technologies to the cost of traditional grid upgrades to accommodate this goal. It found that the net cost of the necessary smart grid upgrades would be DKK 1.6 billion, versus DKK 7.7 billion for traditional grid upgrades (Energinet.dk, 2010).

Sources: Danish Energy Agency, 2012; Wind Power Prognosis, n.d.; Breslin, 2009; Danish Energy Association (n.d.).

usual scenario (European Climate Foundation, 2011, p. 8).

These are not predictions of what *will* happen, but rather scenarios of what is *possible*.

What these studies and others generally conclude is that achieving high levels of renewables will require electricity systems substantially different from those of today. It will be necessary to make these systems much more flexible, responsive and intelligent:

- "Renewable electricity generation from technologies that are commercially available today, *in combination with a more flexible electric system*, is more than adequate to supply 80% of total U.S. electricity generation in 2050" (Hand, *et al*. 2012, p. iii emphasis added).
- "The transition to a low-carbon future that employs high shares of RE may require considerable investment in new RE technologies and infrastructure, including more flexible electricity grids" (Intergovernmental Panel on Climate Change, 2012, p. 103).
- "A sustainable energy system is a smarter, more unified energy system" (IEA, 2012, p. 29).

What does it mean for electricity systems to be flexible and smart? Smart grids use technologies to instantly relay information to match supply with demand, support well-informed decisions, and keep systems operating at optimal efficiency. These technologies can be implemented at the level of generation technologies to consumer appliances. For example, just as a "smart appliance" in a private home can switch on and off in response to varying electricity prices, a "smart transformer" on the grid can allocate power to industries at more reliable prices. The same smart transformer can also automatically notify grid operators and repair personnel if its internal temperatures get too high, while a "smart meter" can measure and track the output of a rooftop photovoltaic (PV) system and send that data back to the utility, to make use of surplus or address gaps due to solar variability as required.

Smart grid technologies offer a long list of benefits, including a more efficiently operated electricity system and reduced operational costs. However, a primary benefit—and the focus of this report—is that smart grid technologies enable high levels of renewables to be included in an electricity system.

Case Study 2: Puerto Rico's smart grid rollout

Puerto Rico has ambitious plans to install as much as 1 Gigawatt (GW) of renewable electricity (excluding hydroelectric) into its 5.8 GW capacity system, with a 3.4 GW peak demand electric grid. As an island, Puerto Rico cannot rely on neighbouring countries or jurisdictions to supply power when the sun is not shining, nor to absorb surplus power when the wind blows strongly. It therefore requires that new RE plants be able to regulate both real power and reactive power output, in addition to performing other smart inverter functions. Solar project developers are complying with this mandate by installing smart inverters with Volt-Ampere Reactive (VAR) control and fault ride-through capability (see Chapter Five), and by including battery storage systems in parallel with PV plants, the first of which were completed in 2012. The economics of energy storage are better in Puerto Rico than in most locations because of the high cost of electricity on its primarily oil-fired grid, which ranges from USD 0.26 per kilowatt-hour (kWh) to over USD 0.30 per kWh.

These RE projects are part of a broad smart grid rollout that began in 2010 and includes distribution automation (DA) with FLISR (i.e., fault location, isolation, and system restoration; see Chapter Five), installation of phasor measurement units (PMUs), demand response (DR), advanced metering infrastructure (AMI) with customer-facing portals, and electric vehicle (EV) infrastructure; all of which are in addition to increasing RE-based power generation and energy storage. Puerto Rico's RE plans include solar PV, wind, landfill gas plants and solid waste–fired plants. Communications and control will be provided by an upgraded radio system and new broadband-over-powerline communications systems. Pilot projects have been initiated for most of these technologies. The AMI pilot, in conjunction with other measures, has already saved USD 17 million per year in reduced electricity theft within the first three years, a figure that is expected to rise to USD 50 million when the AMI rollout is expanded. Puerto Rico has also explicitly adopted a variety of international standards related to smart grid and RE deployment, helping to ensure interoperability of its various systems.

Sources: Autoridad de Energia Electrica de Puerto Rico, 2011; Autoridad de Energia Electrica de Puerto Rico, 2012; Burger, 2012; Cordero, 2010; Puerto Rico Electric Power Authority, 2011; and Romero Barcelo, 2012.

This report is intended as a pragmatic user's guide on how smart grid technologies enable high shares of renewables. The intended audience for this report includes electricity system managers and operators, energy policy analysts and policy-makers, and decision-makers with authority over electricity system investment.

This report is organised as follows:

- Chapter Two provides concrete steps that decision-makers can take to ensure optimal use of smart grid technologies for renewables.
- Chapter Three disentangles the complex relationship between smart grid technologies and renewable electricity generation and explains in detail how smart grid technologies can enable renewables.
- Chapter Four provides an overview of the non-technical barriers to smart grid technologies.
- Chapter Five provides a comprehensive and detailed review of smart grid technologies, including costs, technical status, and applicability. Tables 5A, 5B, and 5C summarise much of this information.

Much of what is known or discussed about smart grids and renewables in the literature is still at the conceptual/visionary stage and it can be challenging to translate these visions into what they mean for a utility or an existing electricity system. To aid this process, we have included several case studies that involve actual, real-world installation and use of smart grid technologies that enable renewables. These case studies were selected to illustrate how smart grid technologies can be used in very different applications—from small islands with ambitious renewables goals, to industrialised countries with high levels of renewables already installed.

Throughout this report, we use the term "utility" to refer to the organisation that operates or manages the electricity system. Depending on the country, this could be a government agency, a vertically integrated regulated private company, an independent system operator (ISO), or even a private company operating in a competitive market.

2. Making the Transition to a Smarter Grid

Smart grid technologies can help enable renewables, but the lack of experience and associated uncertainties—in technology cost and performance, in costs and benefits and in nontechnical issues such as privacy—make it challenging to settle on a strategy that makes best use of these technologies.

The large differences between countries' electricity systems add additional uncertainty. Current levels of renewables share vary across countries ranging from 67% in Latin America to less than 2% in the Middle East. Similarly, national targets for renewables range from modest targets of around 5% to 100% in 2020 in the case of several island states. Also, the electricity system itself has evolved differently across countries depending on their geography, their demand profiles, and their mix of electricity resources. In some regions, such as Europe, electricity demand is expected to stabilise while regions such as Asia and Africa are expected to see electricity demand to double or triple in the next 20 years.

Despite these uncertainties, the REMAP 2030 results have shown that higher shares of renewables will be necessary to achieve the doubling target for renewables in all regions and countries. One of the key questions for decision-makers is therefore when and how to introduce smart grid technologies. To assist policy-makers and others in setting a smart grid and renewables strategy, we provide some specific suggestions that can help guide this process.

Start with Pilot and Demonstration Projects

One logical path forward is to introduce "smartness" into electricity systems incrementally. As shown in Figure 2A, today's largely one-way electricity systems have little or no information flowing from consumers to the utility. At the other end of the spectrum is a fully integrated system that includes several types of distributed resources, advanced pricing and other smart grid-related technologies. Note, however, that there is a wide range of possibilities between these two extremes.

Pilot or demonstration projects that try out smart grid technologies can provide insight into how these technologies perform in a specific system. They can also ease concerns about how the technologies affect reliability, how consumers react, and what it means to open up the electricity system to new actors and new technologies.

Specific Technology Recommendations

Choosing which smart grid technologies to use is a system-specific decision, requiring a detailed look at the current state of an electric system as well as projections of its possible future states. However, some general recommendations can be made.

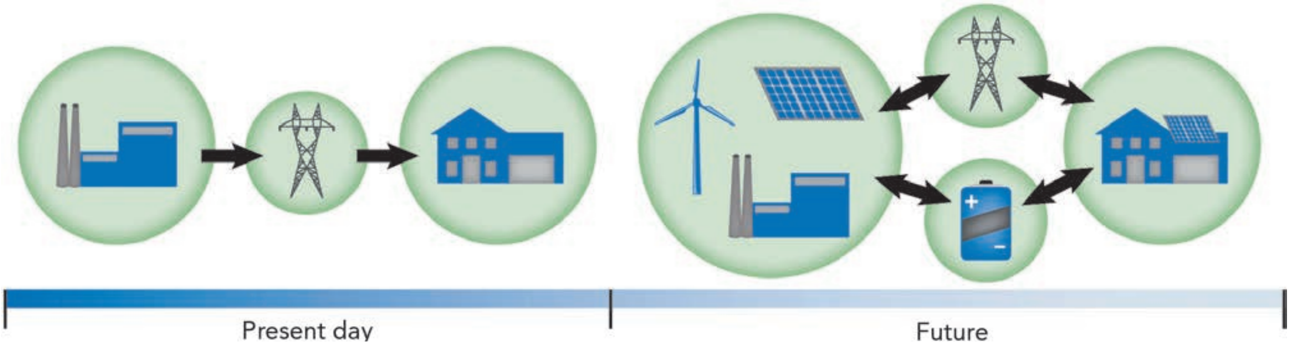


Figure 2A: Visions of the electricity system. Present and future flows.

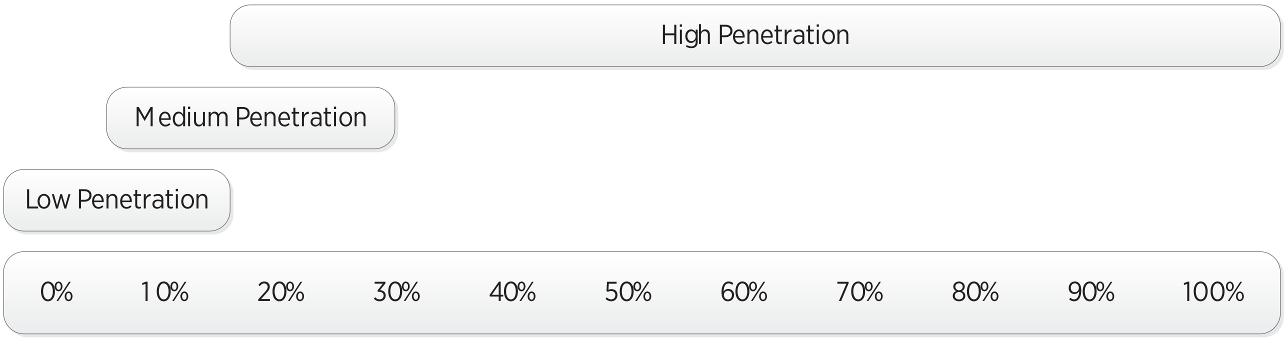


Figure 2B: Approximate ranges of RE penetration

When grid upgrades are required, whether to accommodate RE or for other reasons, it is typically much more cost-effective to include smart grid technologies than to use only conventional technology (see, for example, the Denmark case study in Chapter Five).

It is of course important to choose specific smart grid technologies wisely. Although each electricity system differs depending on the mix of energy sources and geographical demand profiles, we consider three different levels of renewables penetration[1] in electricity systems. The three levels are defined in terms of the grid modifications necessary to accommodate non-dispatchable renewables, rather than in terms of absolute percentage. Low levels of renewables, with capacity penetration not exceeding 15% (on any section of the grid), are generally feasible without any smart grid technologies. At medium levels of renewables penetration, typically between 15% and 30%, smart grid technologies will become increasingly important. Capacity penetration levels above 30% are considered high for renewables and usually require the use of smart grid technologies to ensure reliable grid operation. As illustrated in Figure 2B, these low, medium, and high penetration ranges overlap significantly because they vary by location (Kroposki, 2011).

Based on this rough categorisation, the following general guidelines are for electric systems that are just starting to consider smart grid technologies and RE (see Chapter Five for full descriptions of these technologies):

When first implementing smart grid technologies, start with distribution automation (DA) and demand response (DR). These are well-established technologies that directly enable renewables and are usually cost-effective, even without considering RE-related benefits.

- Under the general category of DR, start with commercial and industrial customers, and use DR for economic reasons, not just for emergencies. Wait until the technology improves before implementing large-scale DR with residential customers. If you think you need a new peaking plant or an energy storage facility, consider using DR instead. It can achieve many of the same benefits as storage and gas peaker plants, but at a much lower cost.
- Under the general category of DA, conservation voltage reduction has been shown to pay off quickly, both in economic terms and with regard to energy conservation.
- Advanced Metering Infrastructure (AMI) and advanced pricing are not strictly necessary for renewables, even at higher penetration levels, but they can be beneficial. Advanced pricing, in particular, can help nudge consumer prices towards the actual costs of production, and thus increase economic efficiency. Both should be assessed carefully, particularly with respect to return on investment and customer acceptance/public relations.
- Smart inverters and renewable forecasting are not generally necessary if RE penetration levels are low (both grid-wide and in each grid section). They become noticeably helpful from around 10% to 15% capacity penetration (on any section) and become essential as capacity penetrations approach 30% (see Chapter 5 for more details).
- Because forecasting is typically provided as a third-party service and can be added at any time, there is no need to incorporate it when RE penetrations are low.
- Smart inverters do not cost much more than conventional inverters and they are quickly becoming standard equipment, so it does make sense to use smart inverters for any new RE installations, even when renewable penetrations are low.

---

[1] *The penetration level of RE on a section of the electric grid is defined as the ratio of peak non-dispatchable RE power to peak load.*

- Distributed storage, microgrids and virtual power plants (VPPs) are generally not “entry level” smart grid technologies and are less well developed. Most utilities should focus on other technologies first, unless they face special circumstances (such as grant funding, high reliability requirements, or remote locations). Technological improvements are expected to improve the financial appeal of these technologies in the future.

Again, these are general recommendations and are not intended to replace system-specific analyses.

Costs and Benefits: Making the Business Case for Smart Grid Technologies

Regardless of regulatory structure, investments in smart grids must make economic sense. There is considerable evidence that the benefits of smart grid technologies consistently outweigh the costs. For example, a meta-analysis of 30 business cases for smart meter projects in 12 countries representing four continents found that on average the net present value of project benefits exceeded the net present value of costs by nearly two to one (King, 2012). Another study of the Middle East and North Africa found that smart grid investments could save the region USD 300 million to USD 1 billion annually while helping realise the region’s large potential for solar power (Northeast Group, 2012). A U.S. study found that potential investments in sustainable technologies, including smart grid and renewables, have a net present value of USD 20 billion to USD 25 billion based solely on benefits to utilities (Rudden and Rudden, 2012).

Any decisions regarding smart grid technology adoption should involve a comprehensive look at the many costs and benefits. Most smart grid projects, especially those that enable RE, provide socio-economic benefits that accrue not solely to the utility system, but also to customers and the local or global community. These broader benefits include economic gains from greater reliability, improved public health due to emissions reductions and long-term environmental and economic gains from low-carbon electricity (McGregor, 2012). Valuing and internalising these external benefits can be difficult, but many studies and reports are available for reference (Baer, Fulton and Mahnovski, 2004; Cornish and Shepard, 2009; Electric Power Research Institute (EPRI) 2011; European Commission 2012b; Giordano, *et al*. 2012; National Energy Technology Laboratory (NETL), 2009). In the U.S. it has become common for regulated utilities to include external benefits when making the business case for smart grid investments. For example, one California utility found that its investments in smart grid and renewables would result in benefits to society worth USD 391 million to USD 1.32 billion and avoid emission of 7.7 million tonnes of carbon dioxide (San Diego Gas & Electric Company, 2011).

Many of the benefits of smart grids and renewables depend largely on how projects are implemented. Effective project planning and execution are key to realising these benefits. It is crucial to perform tests to ensure that smart grid technologies will integrate successfully with legacy hardware and back-office systems before developing a new project. Power system data with good spatial and temporal granularity is important for analysing the potential benefits of smart grid projects. Grid operators considering smart grid projects should start gathering hourly load data as soon as practical, preferably at the feeder level. Once smart grid projects are in progress, success often depends on realising the substantial value of the large amounts of data generated.

In summary: Smart grid technologies can enable renewables, attract private investment and make better use of existing infrastructure. These newer technologies also introduce risk, are undergoing continual refinement and improvement and, in many cases, lack a clear performance history.

Recognise and Respond to Technological Conservatism

One of the greatest barriers to smart grid implementation is the utility’s inherent conservatism. Utilities are traditionally rewarded for providing reliable service and they have few, if any, incentives for implementing new technologies that can be seen as introducing risk of any sort; performance, financial, or political. As a result, utilities are often understandably hesitant to adopt smart grid technologies. In addition, smart grids can be seen as threatening the fundamental business model of the utility: producing and delivering a product (electricity) and charging a price that reflects the cost of production. Here again, it is no surprise that utility enthusiasm for smart grid technologies may be lukewarm at best.

There are several ways to overcome these barriers. Pilot projects can ease discomfort with new technologies. Providing financial incentives (such as allowing for a greater rate of return on certain technology investments, in the case of regulated utilities) is often effective. Technology mandates, such as those requiring the use of a certain technology, are not a desirable approach due to the rapid rate of technological change in the smart grid field.

Leverage the Need for Private Sector Investment

As noted throughout this report, smart grid technologies can act as an enabler for renewables, largely by reducing the negative impacts of renewables' variability. However, smart grid technologies also offer many additional benefits. Two particularly noteworthy benefits are providing a path for private investment into electricity systems and allowing for better/optimal use of existing electricity infrastructure. These two benefits can be of great value to financially constrained electricity systems.

Electricity demand in much of the world—particularly in developing countries—is expected to continue to climb. In many countries, electricity systems already struggle to provide reliable service. Significant investment is needed to upgrade these systems to meet future demand, and this essential capital is unlikely to be available from fiscally challenged governments.

By enabling distributed renewable generation, smart grid technologies can also help attract private sector investment. Distributed renewable generation allows anyone—an investor, an individual user, a commercial or industrial user—to invest private capital in electricity generation. An example of the former would be a company that aggregates demand-side management (DSM) resources and offers them to the utility as a demand-side resource. (There are several examples of private companies successfully doing this.) Similarly, a private company could build rooftop PV systems and lease them to homeowners, overcoming the problem of high capital costs for such systems. (Here again there are numerous examples.) The significance here is that the private sector provides the capital, assumes the technical and financial risk, and provides a previously unavailable resource to the electricity system.

Recognise the Continual Nature of Technological Change

One of the many challenges in smart grid technology adoption is the rapid rate of technological change, particularly in communications and data management technologies. In an industry still using technologies that have changed little in the past 50+ years (steam turbines, overhead power lines on wood poles, and manual meter reading), this is an unsettling situation. It may be tempting to wait for the rate of smart grid technological development to slow; however, that is unlikely. In fact the opposite is expected; as investment in smart grid technologies increases, the rate of technological improvement is likely to accelerate.

Case Study 3: Singapore's Intelligent Energy System

Singapore's electric grid is notable as one of the most reliable in the world, with a System Average Interruption Duration Index of less than 1.5, meaning that on average, a customer will be without power for less than 1.5 minutes per year. This is due largely to the use of sensing and automated controls in the power transmission and distribution systems. Singapore's electric grid includes an extensive two-way Supervisory Control and Data Acquisition system, with DA installed on the majority of substations and feeders.

Singapore began expanding its already fairly smart electric grid in 2010. The first phase of its "Intelligent Energy System" project involved expanding its grid communications network using a combination of radio communications, fibre optics and broadband-over-powerline (BPL) with a view to supporting intelligent buildings, vehicles and sensors, along with and RE uptake. The radio network supports an AMI pilot project used for DR that employs in-home displays, web portals, and dynamic pricing on 30-minute intervals. The AMI/DR pilot has reduced peak residential loads by 3.9% and total energy consumption by 2.4%. The AMI data is also used to locate and respond to outages. Many industrial customers have their own combined heat and power plants, and plans call for increased use of distributed and sustainable energy sources. Future plans also include AMI rollout to remaining customers, as well as integration of advanced energy management systems at residential, commercial and industrial locations.

Singapore is also installing a pilot microgrid project on the smaller island of Pulau Ubin. Currently served by expensive diesel generators, the microgrid will incorporate solar PV generation to reduce emissions. The microgrid is intended to serve as a test bed for other smart grid technologies and to develop local knowledge and experience with advanced grid technologies in preparation for future microgrids on other islands and in commercial settings.

Sources: Gross, 2010; Menon 2011, Singapore Energy Market Authority 2012.

It is pragmatic to consider carefully all the costs and benefits before proceeding, recognising that the technologies will change and that the analysis may need to be redone in a few years with a new set of technology characteristics. Those individuals in information and computing technologies, who are used to decision-making in an environment of rapid technical change, should be brought into the smart grid decision-making process.

In summary: Smart grid technologies can help ease the transition to sustainable electricity systems. These technologies, however, are continually evolving and improving. A flexible and thoughtful smart grid implementation strategy that balances risk and reward, coupled with openness to private sector direct investment in the electricity system, is the most promising approach.

Regulation

One key challenge of smart grids is that their benefits are undeniable but diffused and challenging to define. Therefore, one critical policy response is to devise a regulatory framework that clarifies these benefits, and helps ensure that they flow to the entities providing the upfront investment. For example, a utility can be expected to invest in smart grid technologies only if they are quite confident that the benefits of that investment (notably enabling higher renewable penetration) come with financial benefits. Therefore, regulators must put in place financial incentives structures that appropriately reward smart grid investments. Without such a structure, such investments will not be made.

3. How Smart Grids Enable Renewables

Increasing renewable electricity generation is an essential component in achieving a doubling of the renewable energy share in the global energy mix. Such a transition is technically feasible, but will require upgrades of old grid systems and new innovative solutions to accommodate the different nature of renewable energy generation. In particular, smart grids are able to incorporate the following characteristics:

- *Variability.* Some forms of renewable electricity, notably wind and solar, are dependent on an ever-fluctuating resource (the wind and the sun, respectively). As electricity supply must meet electricity demand at all times, efforts are required to ensure that electricity sources or electricity demand is available that is able to absorb this variability.
- *Distributed generation.* Distributed renewable generation—smaller-scale systems, usually privately owned and operated—represent a new and different business model for electricity. Traditional utilities are often uneasy about allowing such systems to connect to the grid due to concerns over safety, effects on grid stability and operation, and the difficulties in valuing and pricing their generation.
- *High initial cost.* Renewable electricity generating technologies typically have higher first costs and lower operating costs than fossil-fuelled electricity generating technologies. Although renewables may be "cost-effective" on a lifecycle basis, some electricity systems—particularly in developing countries—simply do not have access to sufficient capital to invest in renewables.

Smart grid technologies can directly address these three challenges of renewable electricity generation. In addition, smart grids offer added benefits that can further ease the transition to renewables. This chapter explains how smart grid technologies enable renewables.

Smart Grids and Variability

One of the principal challenges in operating an electricity system is ensuring that the demand for electricity is *always exactly* equal to the supply. It is difficult to store electricity (although the technologies to do so are steadily improving, see International Renewable Energy Agency (IRENA), 2012) and thus electricity system operators must continually adjust the output of power plants to match demand.

Most traditional fossil-fuelled power plants will operate at a set output level and so electricity system operators can generally depend on these plants to provide a steady and predictable amount of electricity. In addition, power plants fuelled by diesel and natural gas are often designed to allow for continual fine-tuning of their electricity output. This makes the challenge of matching electricity supply and demand manageable.

Some forms of renewable electricity, however—notably wind and solar PV—are dependent on a continually fluctuating resource. If the wind slows or clouds obscure the sun, then the output of these plants drops, leaving electricity system operators scrambling to find other sources of electricity.

When wind and solar PV provide a small fraction of total electricity—in the order of a few percent—it is usually straightforward to manage the fluctuations. However, when these "variable resources" begin to provide a significant fraction of the system's total electricity, maintaining system reliability can become increasingly challenging. Even when renewables provide a small fraction of a system's total electricity, they may be providing a large fraction of electricity on a smaller time scale or larger geographic area. For example, wind power provided 57% of a Colorado utility's electricity late one night, although wind on average over the year supplied just 17% (CNN Money, 2012).

Smart grid technologies can do much to help meet that challenge. In essence, a smart grid makes it possible to integrate renewables with a wide range of diverse electricity resources. For instance, imagine a PV system and a set of commercial and industrial electricity consumers on an interruptible rate, all tied together with smart grid communication and control technologies. If the PV system output drops due to a cloud, then the smart grid interrupts service to those customers on the interruptible rate[1]. When the cloud moves on, their service resumes. Similarly, a smart grid could integrate electric vehicles

---

[1] *An interruptible rate is an electricity rate in which service can be interrupted without penalty.*

(EVs) with utility-scale wind turbines so the vehicles' batteries could be charged with wind power.

Smart Grids and Distributed Generation

Distributed renewable generation, notably rooftop PV, is a particularly promising renewable technology. Smart grid technologies can do much to promote greater use of distributed renewable generation. They can provide system operators with continual, real-time *information* on how these systems are operating and allow full *control* over these systems. This information and control can be used in several ways, including, for example:

- Reducing output of, or even disconnecting, distributed generation as needed to maintain reliability, match load, or protect workers.
- Providing real-time data on distributed generation electrical output.
- Supporting the distribution system through, for example, tighter control of voltage.

Utility system operators may be uncomfortable with electricity generation that they cannot monitor and control. Smart grids can provide this monitoring and control and thus encourage utilities to consider distributed renewable generation as an alternative to traditional utility-scale power plants.

Smart grids can also make it possible to more accurately *price* and *value* distributed renewables. Distributed generation can have multiple impacts on distribution systems, from voltage regulation to administrative costs (Hoke and Komor, 2012). Detailed data on distributed renewables' output and performance, such as that available from a smart grid, can help the utility or system operator put an accurate figure on the value of the distributed renewables. Similarly, the data can help the utility determine the proper price to pay the distributed renewable system owners or operators for their systems' output.

Smart Grids and Capital Intensity

Smart grids can help indirectly address the capital requirements of new renewables through encouraging private investment in electricity systems primarily by allowing for distributed renewable generation.

Traditionally, it has been the utility's role and responsibility to build power plants when they are needed. Distributed renewable generation, in contrast, allows anyone—an investor, an individual user, a commercial or industrial user, to invest their own private capital in electricity generation. For capital-strapped utilities, this is an appealing option. Smart grids enable this by providing, in essence, a way for utilities to manage and incorporate many small, individually owned power plants into the electricity system.

A more radical vision of the electricity system of the future—enabled by smart grids—is one in which most or all electricity is provided by distributed generation. Electricity users make direct, bilateral deals with electricity generators and the utility's role is relegated to one of standard-setting and distribution system upkeep. This is somewhat analogous to the Internet, in which governments took some early responsibility to provide the network, but the private sector provides all the content.

Improved Consumer Information, Control, and Choice

Smart meters, a type of smart grid technology, allow for two-way communication between the utility and the consumer. This makes many innovations possible, including, for example:

- Enabling real-time pricing.
- Linking electricity price signals directly to "smart" appliances.
- Providing detailed consumer information on electricity consumption patterns.
- Allowing for different electricity products (for example, programming a plug-in EV to charge only with wind power).

This can encourage renewables by, for example, providing consumers with information that allows them to use electricity only when it is available from renewables. (This will work only with deferrable loads, such as dishwashers and EV charging.)

Improved Transmission and Distribution System Monitoring and Control

Smart grid technologies can allow for fine-grained information from transmission and distribution (T&D) systems. Such information could be used to improve reliability and reduce costs. For example:

- If voltage on a distribution line was found to be low, output from distributed generation systems on that line could be increased.

- If a distribution system component was operating out of specifications, that problem could be addressed before it led to an outage.
- If a country's electricity system experiences electricity theft, such theft could be pinpointed and reduced.

This in turn can help renewables by, for example, matching the output of distributed generation to T&D system needs. Distributed renewables can provide voltage support (Hoke and Komor, 2012) and a smart grid that has improved T&D system monitoring and control can ensure that the two systems work together.

Integration of New Resources

There are several alternatives to traditional, utility-scale power plants. These include:

- Supply-side options, such as distributed generation.
- Demand-side options, such as demand-side management.
- Storage options, such as EVs, batteries, and thermal storage.

Smart grid technologies can allow for optimal use of these alternative technologies, and thus avoid the need for new large power plants. In addition, as previously discussed, these alternatives are generally amenable to direct private sector investment and can help address utility underinvestment and capital constraints.

This eased integration can help enable both utility-scale renewables (such as multi-megawatt wind farms) and smaller distributed renewable generation. New flexible resources such as DSM and distributed storage make it possible to incorporate higher levels of variable resources (such as wind turbines) in a system.

Case Study 4: Jamaica's smart investment to curb losses

Jamaica currently obtains over 90% of its electricity from diesel generators, leading to high electricity prices and a drain on the country's scarce capital. In addition, almost one-fourth of electricity produced in Jamaica is "lost"—10% in the transmission and distribution system and much of the remainder to theft.

Jamaica has ambitious plans to increase the amount of renewables in its system, enhance energy efficiency and reduce losses. A carefully integrated suite of smart grid technologies is helping to achieve those goals. Jamaica has invested USD 50 million annually in T&D upgrades, is spending USD 10 million on AMI and has installed a new Supervisory Control and Data Acquisition system that will enhance renewables integration, support DSM and help pinpoint losses.

Source: Stennet, 2010.

4. Nontechnical Barriers to Smart Grids

Higher renewables shares in the electricity system will not only change the energy source, but can transform the very nature of how electricity grids are operated. Smarter grids will not only be more efficient and ease the way towards a sustainable future, but they also can change the institutional relationships between generators, consumers, and transmission and distribution companies, the way grids are managed and regulated. These nontechnical issues should be recognised when considering a transition to a smarter grid and include:

- *Data ownership and access.* Smart grids increase the amount and availability of data—data that has value. Who owns this data? Who can access the data?
- *Grid security.* How do smart grid technologies affect the electricity system's vulnerability to natural disasters or malicious attack?
- *Control of distributed resources.* Who should control a distributed renewable generator—the owner/operator or the utility/system operator?
- *Role for new market players.* What are the implications of opening up the electricity system to new companies and individuals? How might this opening up affect system reliability, power quality, cost and other variables?
- *Need for standards.* The various components of a smarter grid must be able to communicate with one another. What language should be used, and who makes that decision?

There are no simple answers to these questions and very limited experience worldwide from which to learn.

Data Ownership and Privacy

Consider the example of a smart meter that continually tracks voltage and current on a residential PV system. These data may be of value to:

- The homeowner, with an interest in how the system is performing.
- The utility, with an interest in what contribution the system is making to the electricity grid.
- The installer/manufacturer, to evaluate the PV technology.
- Policy makers and system planners, to better understand the role of PV in electricity systems.

So who "owns" the data? At first glance one might say the homeowners, as they presumably paid for the system. But what if the utility offered a subsidy? And what if the utility needs the data in order to ensure system reliability? Some of these questions can be managed contractually (that is, by written agreements between parties); however, it may be useful to decide up-front who has initial ownership of the data.

A related issue is that of privacy. In some cases, smart grid data may allow an electronic "look" into a business or home. For example, data from net metering of a residential PV system could be used to detect when someone is home, and even what appliances they are using. Homeowners might not want that information publicly available.

This is similar to the ongoing discussions on Internet privacy. Data on an individual's Internet usage—sites visited, goods and services purchased, and the like—might

Case Study 5: New Mexico's Mesa del Sol integrated energy system

One long-term vision for smart grids is to combine a mix of power sources—both renewable and traditional generation—with improved efficiency, with the whole system optimised and integrated through smart grid technologies. A small-scale version of that vision is being tested at a community in Albuquerque, New Mexico. The Mesa del Sol integrated energy system consists of a 50 kW PV system, an 80 kW fuel cell, a 240 kW reciprocating engine-generator, a battery storage system, and advanced building controls for DR. All of these elements are tied together with an advanced communications and control network. The system, once fully installed, will be able to "island" in case the grid goes down; hence, it is a good example of a microgrid. In addition, the system could shift or cut demand on request from the utility, and as such serve as a dispatchable power source.

Source: New Mexico Green Grid, n.d.; Shimizu Corporation, 2012 be tracked. Is this appropriate? Under what conditions can such data be collected and sold—if at all? These questions are still largely unresolved.

Several studies have concluded that consumer privacy must be protected in order for smart grids to achieve social acceptance (see, for example, European Network and Information Security Agency (ENISA) 2012; Colorado Smart Grid Task Force 2011). A recent European Commission recommendation on smart grids noted the importance of protecting privacy and personal data (European Commission 2012a).

Some groups and individuals have raised concerns about the public health impacts of smart meters. The claim is that the electromagnetic fields generated by these meters could have detrimental health impacts. Although there is little scientific evidence for this claim, this issue has led in a small number of cases of communities trying to ban or limit residential installations of smart meters. Given the potential political volatility of this issue, it is prudent for utilities and others to carefully monitor the evidence to ensure that all public exposure and public health requirements are met and carefully monitor public exposure levels.

Grid Security

Smart grid technologies can both increase and decrease grid security. For example, advanced grid monitoring can catch grid problems (such as transmission line failure) early and help make appropriate changes (in this case, shifting loads to other lines), thereby enhancing grid security. On the other hand, a more "open" system (meaning ione in which it is easier to access grid-related data), might lead to easier electronic access to the system, which in itself might cause problems.

Several recent reports (such as ENISA, 2012; and Massachusetts Institute of Technology (MIT), 2011) have provided recommendations as to how grid security can be protected or enhanced with smart grid technologies. One theme of these reports is that grid security must be considered and built in from the earliest design phases of a smart grid project—it cannot be "added on" later.

Control of Distributed Resources

Imagine a distributed PV system for which the PV owner is paid by the kWh. The PV owner therefore has a financial incentive to maximise the PV system output. The utility, however, may at times want to curtail the PV system output for several reasons: to maintain load factors on steam-based power plants, to protect the distribution system, or even to shift electricity production to its own generating facilities. Who gets to control the PV system? This is a complex issue. Some of these situations may be able to be managed contractually; however, it is best to recognise upfront that diverging interests and incentives can lead to conflicts.

The Role of New Private Sector Grid Players

A smart grid "backbone" can attract significant private investment into existing electricity systems. This can help financially constrained utilities improve and extend electricity service by allowing the private sector to make the much needed capital investments in renewable technologies.

However, this will only work if the utility—and regulators—are willing to allow private sector organisations some control and potential for profit. A useful first step is for the relevant stakeholders—regulators, utilities and potential private sector investors—to meet and present their interests and concerns *before* trying to implement a project.

Case Study 6: PowerMatching City in the Netherlands

The advanced vision of a fully decentralised, technology-intensive smart grid system is nicely illustrated by the "PowerMatching City" demonstration project in Hoogkerk, the Netherlands. This very high-technology project involves 25 residences and a range of advanced technologies, some of which have household-sized combined heat and power units that use natural gas to generate electricity and heat. These units have a peak electrical output of 1 kilowatt (kW). Each household has a 1.6 kilowatt-peak (kWp) PV system. Air-to-water heat pumps are used for space heating. Smart washing machines and dishwashers, which operate when electricity costs are low, help shift electricity demand to off-peak periods. There are also pure electric and hybrid-EVs. All components are integrated via a common communications system.

Source: Bliek, et al., 2010

The Need for Standards

Imagine an electricity system for which there is no common standard or agreement on end-use voltage, frequency, or even plug shape and size. Small groups of users and manufacturers would try to come to agreement on a set of standards, but even if they succeeded, there might be multiple standards in existence. Such a system would clearly not function well.

This is analogous to the current smart grid situation. There is considerable ongoing work to establish a universal, widely agreed-upon set of standards that establish and define how different components communicate and connect. In Europe, organisations involved in this effort include the European Committee for Standardization (CEN), European Committee for Electrotechnical Standardization (CENELEC), and European Telecommunications Standards Institute (ETSI) (CEN, 2012), whereas in the U.S. much of this work is being coordinated by the National Institute of Standards and Technology (NIST, n.d.).

It is not necessary for individual utilities or decision-makers to get involved in the actual standards-setting process. However, it is advisable to monitor the outcomes from these committees to stay current with emerging standards.

5. Smart Grid Technologies

There is no universal agreement on what qualifies as a smart grid technology; however, it is generally understood to include a wide range of communication, information management and control technologies that contribute to the efficiency and flexibility of an electricity system's operation. These technologies can be put into four functional categories (see Figure 5A).

- *Information collectors:* Smart grids are based on data that is collected from various types of sensors. These sensors generally measure performance-related characteristics of electricity system components. Examples include meters that continually measure the power and electricity output of a distributed renewable generator; sensors that track temperature, vibration and other characteristics of a transformer; and meters that measure electricity characteristics (voltage, current, etc.) of a distribution line.
- *Information assemblers, displayers, and assessors:* This category includes devices that accept information and display and/or analyse it.
- *Information-based controllers:* These devices receive information and use it to control the behaviour of other devices to achieve some goals, such as reduction of electricity expenditure or stabilisation of a voltage.
- *Energy/power resources:* These include technologies that can generate, store, or reduce demand for electricity.

Smart grid technologies vary widely in cost, applicability, and market maturity. Nevertheless, a carefully integrated set of smart grid technologies can decrease the costs and risks of integrating distributed renewables into electricity systems.

The following discussion provides details on the purpose of specific smart grid technologies, their strengths and weaknesses, their current status and other relevant information. We focus on technologies that apply at the distribution level, as these technologies are underutilised and show great potential. The technologies are presented in order of decreasing technological maturity, with a final section briefly describing bulk power technologies of varying maturity.

The information is summarised in Tables 5A and 5B. Both tables list the technologies in order of decreasing technological maturity. Table 5A summarises maturity, availability/market penetration, economics, and down-

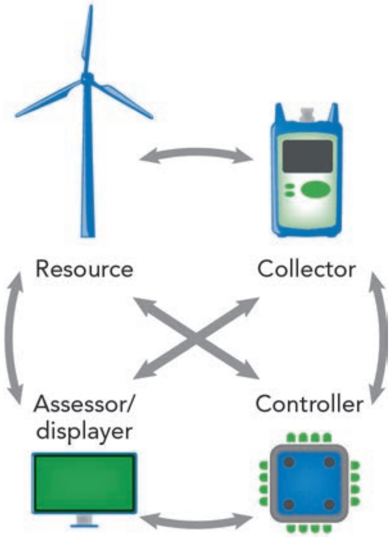
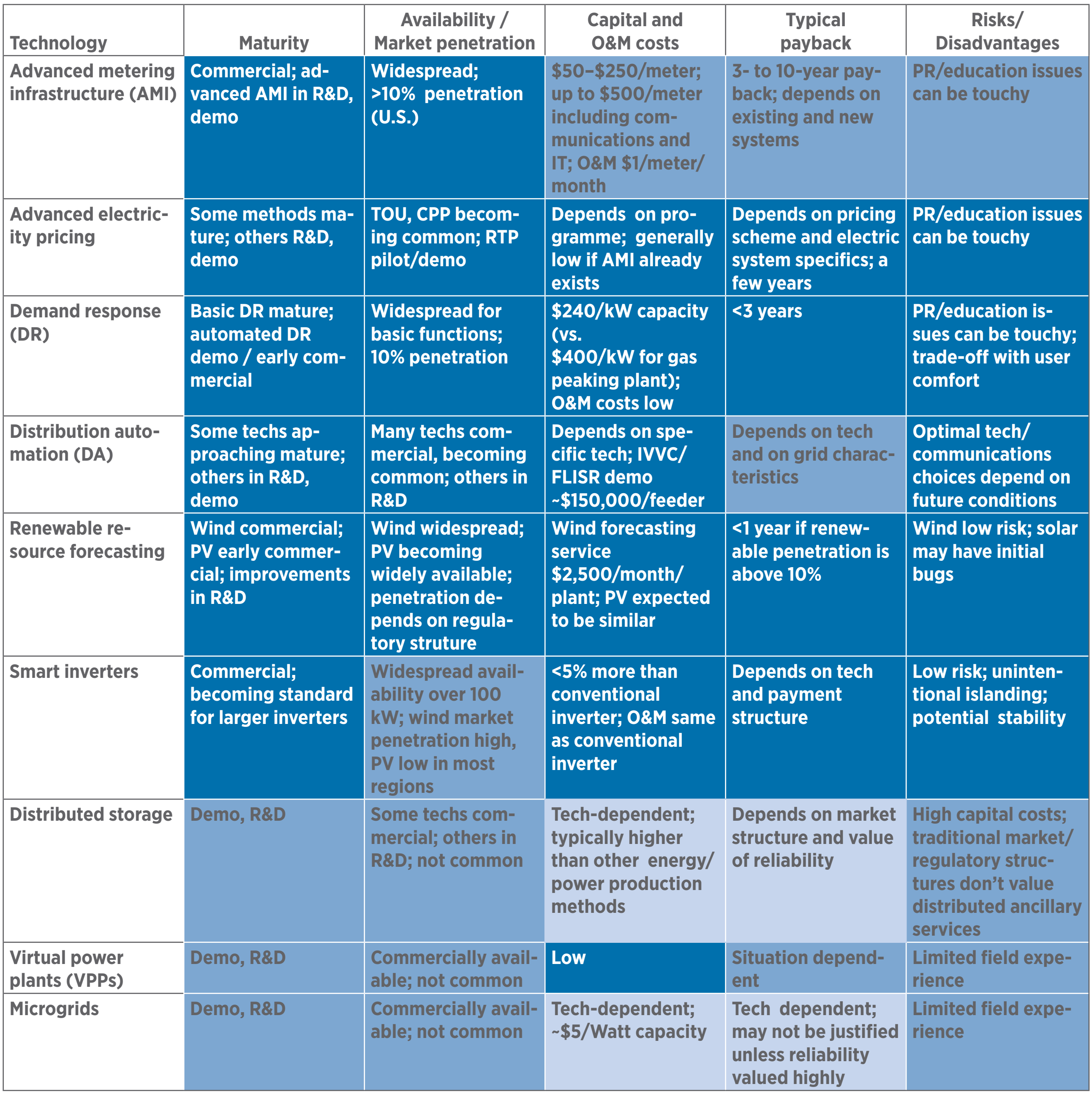


Figure 5A: The four functions of smart grid technologies

Table 5A: Smart grid technology summary, part 1



Technology	Maturity	Availability / Market penetration	Capital and O&M costs	Typical payback	Risks/ Disadvantages
Advanced metering infrastructure (AMI)	Commercial; advanced AMI in R&D, demo	Widespread; >10% penetration (U.S.)	\$50–\$250/meter; up to \$500/meter including communications and IT; O&M \$1/meter/month	3- to 10-year payback; depends on existing and new systems	PR/education issues can be touchy
Advanced electricity pricing	Some methods mature; others R&D, demo	TOU, CPP becoming common; RTP pilot/demo	Depends on programme; generally low if AMI already exists	Depends on pricing scheme and electric system specifics; a few years	PR/education issues can be touchy
Demand response (DR)	Basic DR mature; automated DR demo / early commercial	Widespread for basic functions; 10% penetration	\$240/kW capacity (vs. \$400/kW for gas peaking plant); O&M costs low	<3 years	PR/education issues can be touchy; trade-off with user comfort
Distribution automation (DA)	Some techs approaching mature; others in R&D, demo	Many techs commercial, becoming common; others in R&D	Depends on specific tech; IVVC/ FLISR demo ~\$150,000/feeder	Depends on tech and on grid characteristics	Optimal tech/ communications choices depend on future conditions
Renewable resource forecasting	Wind commercial; PV early commercial; improvements in R&D	Wind widespread; PV becoming widely available; penetration depends on regulatory struture	Wind forecasting service \$2,500/month/ plant; PV expected to be similar	<1 year if renewable penetration is above 10%	Wind low risk; solar may have initial bugs
Smart inverters	Commercial; becoming standard for larger inverters	Widespread availability over 100 kW; wind market penetration high, PV low in most regions	<5% more than conventional inverter; O&M same as conventional inverter	Depends on tech and payment structure	Low risk; unintentional islanding; potential stability
Distributed storage	Demo, R&D	Some techs commercial; others in R&D; not common	Tech-dependent; typically higher than other energy/ power production methods	Depends on market structure and value of reliability	High capital costs; traditional market/ regulatory structures don't value distributed ancillary services
Virtual power plants (VPPs)	Demo, R&D	Commercially available; not common	Low	Situation dependent	Limited field experience
Microgrids	Demo, R&D	Commercially available; not common	Tech-dependent; ~\$5/Watt capacity	Tech dependent; may not be justified unless reliability valued highly	Limited field experience

Key: Colors indicate qualitative rating of each technology:

Generally positive, at least in some cases
Generally neutral
Generally negative

\$ = USD (United States Dollars), ~ = Approximately, Refer to List of Abbreviations at end of report for other definitions

Where: O&M is Operation and Maintenance; R&D is Research and Development; TOU is Time of Use; CPP is Critical Peak Pricing; RTP is Real-Time Pricing; IVVC is Integrated Volt-VAR Control.

sides of each technology. It is colour-coded to indicate whether each attribute generally reflects positively (dark blue), neutrally (blue), or negatively (light blue) on each technology. These ratings are general guidelines only; specifics will vary widely with system details. Table 5B summarises additional descriptive aspects of each technology. An additional table, 5C, is included in the section on bulk power–oriented technologies.

Table 5B: Smart grid technology summary, part 2

Technology	Problems mitigated	Time scale	Grid type applicability[1]	Depends on existence of[2]	Synergistic with
Advanced metering infrastructure (AMI)	Lack of distribution monitoring; outage detection and location; energy conservation; energy theft	Current: min, hr, day; future: millisec, sec	All	Standardisation; interoperability	DR; advanced pricing; DA
Advanced electricity pricing	High peak loads; load shedding; outage frequency	Current: 5-min, hr, day; future: sec, min	All	AMI	Smart inverters; forecasting
Demand response (DR)	High peak loads/ prices; load shedding; outage frequency	Current: 5-min, hr, day; future: sec, min	All	Communications, e.g. AMI; smart equipment/ thermostats; favourable regulatory environment	Smart inverters; AMI; advanced pricing; microgrids/ VPPs
Distribution automation (DA)	Inefficiency; voltage regulation; outage frequency and duration; distribution maintenance costs	Sub-sec, sec, min, hr	All	Standardisation, interoperability	AMI; DR; distributed storage; smart inverters; PV forecasting; microgrids
Renewable resource forecasting	Reliability issues and cost of wind/ solar variability; voltage and frequency regulation	Current: 5-min, hr, day; future: sec (PV)	>10% RE	Local service availability	Microgrids & VPPs; DA; advanced pricing; storage
Smart inverters	Power quality; voltage/frequency regulation; undesired inverter tripping offline	Millisec, sec, min, hr	All	Favourable regulatory environment	DR; AMI; advanced pricing; microgrids; VPPs
Distributed storage	Voltage/frequency regulation; power ramps	Millisec, sec, min, hr	>20%–30% RE	Not applicable	AMI; advanced pricing; DA; microgrids; VPPs; forecasting
Virtual power plants (VPPs)	Solar/wind variability; high peak loads/prices	All	Significant distributed resources	Favourable regulatory environment	Smart inverters; distributed storage; advanced pricing; DA; forecasting
Microgrids	Power outages; power quality; solar/wind variability; high peak loads/ prices	All	Significant distributed resources	Favourable regulatory environment	Smart inverters; distributed storage; advanced pricing; DA; forecasting

Note 1: All technologies listed can be applied to most electric grids to some extent. Grid types listed here are those for which a technology may be particularly beneficial.

Note 2: All technologies depend to some extent on the regulatory environment and on standardisation and interoperability issues. These dependencies are only listed here if they may be particularly problematic for the technology in question.

Advanced Metering Infrastructure

AMI refers to smart electricity meters and the communications and data processing equipment needed to collect smart meter data and deliver it to the grid operator (King, 2005). Smart electricity meters differ from conventional electricity meters in three ways:

- They measure energy usage with higher time resolution (typically in less than one-hour intervals).
- They communicate usage data back to the utility regularly (typically, at least once a day, but often much more frequently, *e.g.* up to real-time transmission).

- They are capable of two-way communication with the utility.

Smart meters include both customer meters and meters used to monitor the electricity system, including those that measure RE output.

Communications may occur over a wide variety of media, including Internet, radio, Wi-Fi, BPL, cell modem, or satellite. Communications networks may be traditional fixed networks or flexible mesh networks. Information communicated from the utility to the meter may include price signals, connect/disconnect signals and DR information.

AMI enables several smart grid technologies that facilitate renewable power (Leeds, 2009):

- AMI can measure renewable resource output, including ancillary services, for compensation, control and planning.
- AMI can serve as the communications infrastructure to integrate distributed resources into DA schemes.
- AMI enables advanced electricity pricing schemes, which can improve the economics of distributed PV.
- AMI can serve as the communication link that enables DR, which is synergistic with PV.

A variety of specific functions are performed by some, but not all, smart meters:

- Smart meters may collect data on power quality, power outages, power factor, reactive power usage, and grid voltage and frequency. This information may be useful for DA, a technology described in full later.
- AMI may also include customer-facing portals, providing customers with detailed energy usage data. This data may help customers conserve energy or shift energy usage to off-peak times, as described in the section on advanced electricity pricing.
- A smart meter may serve as a communications gateway to enable DR, as discussed further later in this text.

AMI systems are becoming common in industrialised countries. Pike Research reports that more than 70 million smart meters were sold globally in 2011 (Strother and Gohn, 2012). However, many of the more advanced smart meter functions mentioned above are not yet common. AMI systems typically cost less than USD 500 per meter including communications and information technology components, and financial payback periods are in the range of three to ten years (Sandlin, 2009); the smart meter is the major cost component (Chan, *et al.*, 2012).

As with all smart grid products, the interoperability of smart meters with a utility's existing systems is a challenge. Because standardised interoperability testing programs have yet to be developed, utilities should expect to run their own tests to ensure that new products will integrate well into their existing hardware and back-office systems.

One of the benefits of smart meters is that utilities no longer need to send workers out to read meters. This benefit is also offered by automatic meter reading (AMR) systems that do not necessarily involve smart meters. At least one utility reports that if AMR is not already implemented, the economic case for AMI is good, but if AMR has been installed, the economic payback of AMI is not ensured (MetaVu, 2011). The economics of AMI are expected to improve as the technology matures.

Technologies that take advantage of AMI are changing quickly. With this in mind, utilities should carefully evaluate the flexibility and upgradeability of smart meters before installation.

Advanced Electricity Pricing

Electric power plants are generally dispatched so that the plants with the lowest operating costs (baseload plants) come on first, followed by more expensive plants when load increases, and finally, the most expensive plants during times of peak load[1]. Very little electricity is stored for future use because storage is typically too costly. For this reason the marginal cost of supplying electricity is much higher during times of peak load. However, most electricity consumers are charged the same price for every kWh they consume. This is economically inefficient as the prices consumers pay do not reflect the true costs of production.

Advanced electricity pricing refers to a broad range of approaches and pricing programmes that try to make consumer prices more accurately reflect real-time production costs so that customers shift consumption toward times when electricity is less expensive. Advanced pricing can also shift consumption to times when RE is available. Three representative advanced pricing schemes are described further.

---

[1] *Dispatch of power plants involves other considerations beyond operating costs, including the ease with which plants can be turned on and off, but it remains generally true that peaking plants are the most expensive to operate and baseload plants the cheapest.*

Time-of-Use Pricing

Electricity usage typically peaks around the same time every day in a given area. The simplest method of discouraging electricity use during peak times is to institute a time-of-use (TOU) price schedule, under which electricity is least expensive when loads are low (typically at night) and most expensive during peak times (usually afternoons). Customers paying TOU rates may adjust loads manually or use building or home energy management systems (BEMS/HEMS) to control their loads. TOU pricing schemes may vary with the season but are generally set far in advance. This means TOU pricing does not help much on the few days per year when load approaches its annual peak.

TOU pricing programmes are becoming common. TOU pricing is typically advantageous for solar PV, which produces power during the daytime, when the price is usually high.

Critical Peak Pricing

Critical peak pricing (CPP) is a dynamic pricing programme in which utilities signal customers when loads are approaching (or are expected to approach) annual peaks. Customers who respond by reducing loads are compensated. Often, customers are notified a day in advance based on demand forecasts (Levin, 2012). For instance, if a hot cloudy day is expected to result in high air-conditioning loads and low PV production, CPP can be used to reduce the peak load. As with TOU pricing, CPP customers may adjust loads manually or use BEMS/HEMS to manage loads automatically.

Real-Time Pricing

Real-time pricing (RTP) involves adjusting price profile forecasts at intervals throughout the day (Faruqui 2012). These price profiles typically cover the next few hours or days and are updated regularly (at intervals ranging from five minutes to hourly). The time resolution of the price profiles themselves also ranges from five minutes to a few hours. RTP programmes are currently being piloted. These fairly complex pricing schemes require customers to have smart loads or BEMS/HEMS to make adjustments based on dynamic price signals. Real-time pricing is sometimes called dynamic pricing.

RTP signals are able to provide a better approximation of real-time power production costs than other advanced pricing schemes. RTP is particularly well suited to variable renewables such as wind and solar PV, as the output of these resources may not follow an easily predictable pattern.

Distributed Ancillary Service Compensation

Provision of ancillary services (such as voltage and frequency regulation) by distributed resources including renewables is not expected to occur outside of pilot projects until new advanced pricing schemes for distributed ancillary services are developed. Smart grid technologies discussed further in the following text that could provide ancillary services include DR, smart inverters, distributed and bulk storage, microgrids, VPPs and flexible alternating current (AC) transmission systems.

Pricing Scheme Considerations

A wide variety of other pricing schemes have been implemented, and even more are possible. For example, in some regions, EVs are subject to specific electricity rates.

Conventional electric meters only measure cumulative electricity usage, so advanced pricing programmes require smart meters that can record how much electricity was used and at what time.

A meta-analysis of studies of pricing schemes in the U.S., Canada, the European Union and Australia found that TOU pricing typically reduces peak loads by 3% to 6%, while CPP typically reduces peak loads by 12% to 38% (Faruqui, 2010). Benefits of both schemes were greater for customers who used enabling technologies (customer-facing energy usage portals, BEMS/HEMS, smart loads, etc.).

Under well-designed advanced pricing schemes, average electricity rates should be lower than under flat pricing, because use of expensive peak electricity is reduced (Doris and Peterson, 2011). However, some customers will pay more than before the implementation, and others will pay less. This has led to dissatisfaction among those who pay more. It is possible to mitigate this problem by communicating clearly with customers before and during implementation of advanced pricing (Wright, 2011).

As the electric grid becomes smarter and incorporates more renewables, continued adjustment and innovation of pricing schemes will be needed to optimise efficiency and reduce costs. Utilities with high penetrations of wind energy, which often produces more power at night, are already changing the way they think about power plants: baseload plants that run 24 hours per day almost every day are less useful in areas where wind meets a significant portion of the night time load. Fortunately, once appropriate smart meters have been installed, changing pricing plans becomes a matter of business processes and customer relations rather than hardware installation.

Demand Response

DR, also called DSM, refers to techniques for reducing electric system loads during times of peak electricity usage or when renewable output drops (Hedrick, 2012)[2]. The benefits of DR include avoiding the use of the most expensive bulk generation plants, avoiding construction of additional generation and transmission capacity, and avoiding brownouts and blackouts.

DR can directly enable renewables by allowing electricity demand to be controllable, much the way a dispatchable power plant can be controlled. If, for example, the output of a PV power plant drops due to clouds, a DR programme can trigger reductions in electricity demand, thereby avoiding the need for dispatching power plants, reducing the need for spinning reserves, and maintaining power quality (Clean Energy Prospector, 2012).

There are three general categories of DR: direct load control (DLC), voluntary load reduction, and dynamic demand.

Direct Load Control

DLC involves giving utilities limited control of selected customer loads under contracts that provide compensation to the customers. This technique is generally used with large commercial and industrial customers. In some cases customers use on-site generation rather than curtailing loads. DR programmes can also be configured so that grid operators can turn *on* customer loads during times of low system load to avoid having to cycle central generation plants below minimum values. In these cases, customers could also charge storage systems, saving energy for later use. DLC programmes reduce customer autonomy, requiring customers to trade comfort or convenience for monetary incentives, while offering utilities certainty that loads will be reduced when needed.

Voluntary Load Reduction

Voluntary load reduction involves sending signals incentivising customers to reduce their own power consumption voluntarily. This can be a simple on/off signal indicating that reduced consumption during a specific time frame will be compensated financially (as in CPP), or it can be a time-linked electricity price signal where high prices are used to discourage electricity usage and low prices are used to encourage usage (as in RTP). Customer-facing portals showing electricity usage and energy costs can also play a part in voluntary load reduction. As with DLC, customers trade comfort or convenience for economic benefits, but voluntary load reduction preserves customer autonomy.

Although exact amounts of load reduction are not as certain as with DLC, large enough groups of customers in voluntary DR programmes can provide reliable and predictable load reduction within some range. Customers may manually adjust their consumption, or they may use BEMS/HEMS to respond to price signals automatically. BEMS technology, used in commercial and industrial buildings, is more mature than HEMS technology, which is used residentially. Current HEMS systems are expensive and may not be economical unless differences between high and low electricity prices are large.

Dynamic Demand

Dynamic demand is a less common DR technique in which loads automatically adjust their power usage—or their start and stop timing—by sensing grid frequency, with the goal of helping stabilise frequency[3]. Challenges to this technology include reaching enough installed capacity to have a measureable effect and finding ways to compensate customers who implement it.

Demand Response Status

A utility's peak annual load typically occurs only a few hours per year, so reducing loads during only a few hours can avoid the need for gigawatts of generation capacity (effectively eliminating the need for multiple power plants). Hence, a DR programme can act as a virtual peaking power plant (as described below in the section on VPPs) (Wonderware, 2012). In fact, a typical natural gas peaking plant takes 30 minutes to ramp to full capacity, whereas a DR virtual peaking plant can ramp to full capacity in five minutes using current technology and may be able to ramp even faster in the future.

The ability of DR to ramp quickly helps it to mitigate the variability of renewable resources. In fact, there can be a very strong synergy between DR and PV. Typically, the number of hours per day during which customer loads can be reduced is limited. PV often can cover peak loads during midday and early afternoon, freeing up DR to be

---

[2] *Sometimes a distinction is drawn between DR and DSM, with DR referring to direct utility control of customer loads and DSM referring to customer management of loads in response to price signals. However, it is more typical to use the terms interchangeably to refer to any or all of the techniques mentioned in this section (Smith and Quibell, 2010).*

[3] *Increases in load decrease grid frequency slightly, whereas decreases in load increase grid frequency slightly. Conversely, increases in generated power cause increases in grid frequency and decreases in generation cause decreases in frequency. This is known as droop speed control or power-frequency droop and it is fundamental to the operation of the power grid.*

used in late afternoon and evening[4]. As shown in a study of the New York State power grid, combining PV with DR can triple DR's effective load reduction potential (Perez and Hoff, 2008).

The basic DR technology has been around since the 1970s. It has primarily been used with commercial and industrial customers, but smart grid technologies are both expanding DR to residential customers and improving the usefulness of DR. Early DR programmes focussed on use during emergencies to avoid blackouts. More advanced DR programmes now use DR for purely economic reasons, such as to avoid operating expensive peaking plants. As the economic use of DR becomes common, the next advancement in the pipeline is to use DR for ancillary services such as frequency regulation. These advanced types of DR typically require automation of customer responses. This is referred to as automated demand response (ADR).

The lack of mature standardised protocols for advanced DR has been an obstacle. Standards are being developed, including the recently published OpenADR standard[5]. Compensation schemes for advanced DR are also in development. Enrolment of customers in DR programmes is generally voluntary; some customers prefer not to enrol due to privacy concerns, but DR programmes are typically able to save money both for customers and the utilities.

DR may be managed internally by the utility or it may be provided as a service by a third party that aggregates customers and sells the load reduction service to the utility. Third-party DR management may help expand it to more residential customers, because it relieves utilities from having to manage thousands of individual locations. Third-party DR integrated with real-time PV output is beginning to be offered commercially as a pilot project in the United Kingdom.

The market for DR is growing fast and business models are maturing. In the U.S. it is estimated that over 7% of electric power during times of peak load could be supplied by DR, although only about 10% of U.S. customers are enrolled in DR programmes (Federal Energy Regulatory Commission (FERC), 2011).

Capital costs and operations and maintenance (O&M) requirements for DR programmes are quite low compared to other options for matching load with generation, such as peaking power plants or energy storage. Setup costs—including installation of sensors, control systems and software—are less than USD 300 per kW of capacity (Martinez, 2004), considerably less than the cost of new natural gas peaking plants.

Distribution Automation

In general, "DA" refers to various automated control techniques that optimise the performance of power distribution networks (PowerPartners, n.d.)[6]. In contrast to transmission networks, electrical distribution networks have historically not included much sensing and control outside the substation. It is now becoming more common to implement the smart grid DA techniques summarised next.

DA is considered a core part of a smart grid, interacting with almost all other smart grid applications and making the grid more efficient and reliable. DA helps enable RE by dynamically adjusting distribution controls to accommodate variability, power ramping and bidirectional power flows. In addition, some smart inverters may become controllable DA assets themselves.

Volt/Volt-Ampere Reactive Control and Optimisation

Distribution system voltage typically drops as power lines (feeders) get farther from the substation. In order for end-of-line voltages to be above their minimum values, beginning-of-line voltages may need to be near the top of the allowable range. Loads and distributed generation are constantly changing this voltage profile. Devices such as load tap changing transformers, voltage regulators and switched capacitor banks are used to adjust voltage when needed. Reactive power (also known as VARs) can be injected by switching shunt capacitors into the circuit, which raises voltage. Distributed generation and static VAR compensators (SVCs) are also beginning to be used for feeder voltage control. Sensing voltage and power factor at various points in the circuit allows automated, integrated control of these voltage-regulating devices. This is sometimes called integrated volt-VAR control (IVVC) (Wakefield, 2011).

Feeder voltages can also be optimised to increase efficiency. The power consumed by a load is the product of its voltage and current. Hence, reducing voltage reduces power consumed (for many types of loads). Real-time sensing and control of voltage at various points in a distribution circuit can allow voltage to be regulated to near its minimum value throughout the circuit. Known

---

[4] *Note however that PV alone typically cannot provide highly reliable peak load reduction, due to variations in weather (Glassmire, Komor and Lilienthal, 2012).*

[5] *See www.OpenADR.org for more information.*

[6] *Exactly what techniques are included in DA is dependent on who is using the term. This summary interprets the term broadly, following an Institute of Electrical and Electronics Engineers (IEEE) tutorial (IEEE/Power and Energy Society (PES), 2007/2008).*

as conservation voltage reduction, this simple and low-cost technique yields energy savings in the range of 5% to 10%.

Smart inverters, described below, can allow renewable resources to participate in techniques such as IVVC and conservation voltage reduction; however the control systems to achieve this are still in development.

Automated Fault Location and Restoration

Distribution networks use switches and breakers to isolate faults from the rest of the circuit, limiting the number of customers affected (for example, when a branch from a tree falls on power lines). Devices called reclosers, which can open temporarily and then re-close after a brief time, can reduce the impact of temporary faults. Historically, breakers, switches, and reclosers are not monitored or intelligently controlled. Adding sensing to these devices and controlling them using intelligent algorithms can reduce the frequency and duration of outages even further by locating faults more accurately and isolating smaller sections of the grid. Feeders can be reconfigured automatically to route power around fault locations. Intelligent control of switches and reclosers also helps ensure they operate properly in cases of reverse power flow that may occur with distributed resources. These technologies are sometimes referred to as FLISR (*i.e.* fault location, isolation, and system restoration).

Operations and Maintenance Savings

Incorporating sensing and control into distribution equipment can result in O&M savings. For example, failure of transformers can be predicted through advanced monitoring so that replacement can be scheduled before the device fails and causes an outage. Installation of distributed energy can change distribution device stresses significantly and in a way that is difficult to accurately predict, making asset monitoring particularly valuable. When detailed information is available on the condition and usage of distribution equipment, utilisation can be improved and upgrades can be deferred. When outages do occur, they can be located faster and more accurately if sensors are in place; traditionally, utilities rely on customers calling in to report outages. Finally, DA systems reduce the need for manual operation of distribution switches.

Distributed Resource Integration

Distributed energy resources, including renewables and energy storage, can be integrated into DA control algorithms, especially if they are equipped with smart inverters. Dispatchable resources can be used to provide power locally, reducing line losses and equipment stresses. RE forecasts can be integrated into distribution operations, allowing for optimised operations. In general, these technologies are the least well integrated into current DA systems.

Many utilities have implemented pilot projects involving one or more DA technologies. One project reported combined capital costs for IVVC and FLISR of USD 150,000 per feeder. Evaluated against more traditional methods of improving distribution reliability, DA is reported to be several times more cost-effective and utilities continue to move towards it (Institute of Electrical and Electronics Engineers (IEEE)/ Power and Energy Society (PES), 2007/2008). However, at least one utility has reported that DA technologies make economic sense only when replacing distribution devices at the end of their life spans (MetaVu, 2011). It is also important to carefully evaluate present and future communications needs when installing DA in order to select appropriate and cost-effective communication methods. Standardisation of communications and product testing for DA components is in progress but not complete, so utilities should plan to expend some effort ensuring that DA devices work together properly.

Similar technologies, when applied to the electric grid as a whole (including the generation and transmission systems) may be referred to as grid optimisation and carry similar benefits. However, the return on investment is typically larger on distribution circuits because transmission and bulk generation typically already incorporate some degree of sensing and control capability.

Renewable Resource Forecasting

Accurate forecasting and nowcasting of power output from wind and solar resources can alleviate many of the cost and operational challenges related to their variability and increase the value of RE, because power predictions become more certain. Different forecasting methods are used for two future time ranges:

- *One- to two-day-ahead predictions* are made using numerical weather prediction (NWP) models. NWP models have time resolutions in the range of one to three hours and spatial resolutions of 1 kilometre or more. NWP uses physics-based models to process large amount of data and extrapolate future weather from current conditions at meteorological towers. High-performance computers are required, and there is typically a "blind spot" that extends a few hours past the present during which time NWP may not be more accurate than simply assuming future weather will be identical to present weather. Geographical and topological data can be incorporated in NWP modelling to reduce error.

- *One- to six-hour-ahead predictions,* also called nowcasting, are made using statistical models that forecast future weather based on real-time local conditions. Historical weather statistics are used to predict future weather with 15-minute time resolution. Newer techniques bringing time resolution down to five minutes are becoming more common. Current error rates of about 30% for short-term, high-resolution nowcasts are expected to improve.

For both time ranges it is important that wind and solar power predictions include uncertainty estimates so that contingency power reserves can be scheduled efficiently. Some techniques for integration of forecasts into grid operations and control are available, and improved techniques are in development. It is preferable for both wind and solar forecasts to be integrated together into grid operations; techniques to do so are emerging. In areas where solar and wind penetrations are low (<10%), forecasting is not economical due to low return on investment (Lew, 2011).

Wind and solar forecasting are typically sold as services rather than performed internally by grid operators and cost about USD 2 500 per month per plant (Asmus, 2010). The prevalence of forecasting in a given area depends on the penetration of variable renewables and on the regulatory structure. Typical European regulatory structures remove some of the incentive to use accurate forecasting by transferring the costs of variability to the public. In some areas of the world RE forecasting may require better weather data than is readily available. In areas of high renewable penetration and where contravening regulatory structures do not exist, forecasting is typically considered indispensable.

Wind Forecasting

Wind plant power forecasting has become a priority for grid operators as utility-scale wind plants have come to make up a significant portion of grid capacity in some areas. With wind penetrations around 25%, studies have shown that wind forecasting can save tens to hundreds of millions of dollars per year in operating costs over several states in the U.S. (Lew, *et al*., 2011).

When NWP power forecasts for regional aggregations of wind plants are compared to actual wind power output for those aggregations, error rates of 5% are typical. Error rates for single locations are two to four times higher. Current day-ahead NWP error rates are not expected to drop significantly.

Wind plants may also use very short-term (millisecond-scale) wind nowcasting to optimise power output by dynamically adjusting the pitch of turbine blades (Madrigal, 2010). Light Detection and Ranging (LIDAR) and Sonic Detection and Ranging (SODAR) wind sensors located on turbines are used for this purpose. This technology is experimental.

Solar Photovoltaic Forecasting

Solar power forecasting is less mature than wind power forecasting, but is expected to mature quickly as grid penetration levels increase (Ahlstrom and Kankiewiez, 2009). Wind forecasting providers are beginning to expand into solar forecasting. Solar forecasting is already in use by utilities that have large PV plants, but because most solar power variation is due to visible clouds, satellite imagery can be used in addition to traditional weather prediction methods.

Day-ahead NWP solar forecast models have the advantage of easy validation using satellite cloud imagery. Statistical forecasting over the next several hours also relies on satellite imaging as a model input. An additional level of short-term, near-real-time forecasting is available for PV, again using satellite imagery. Near-real-time forecasting can also be performed using ground-based sky imaging to predict output power over the next 10 to 30 minutes. This technology is currently being piloted at a cost of USD 12,000 per PV plant (Postelwait, 2011).

Forecasting has not yet been applied commercially to distributed PV because distributed PV penetrations are typically low, but there will be value in forecasting distributed PV power if penetrations become higher. Microgrids and VPPs (discussed later) are more likely to contain large amounts of PV capacity relative to their overall capacity, so forecasting of distributed PV power will first become economical in these settings (Carson, 2011). It will in fact be difficult to operate a microgrid containing significant PV in islanded mode *without* the ability to forecast PV output. For VPPs with significant PV or wind, the value of the VPP to the overall grid will hinge on accurate forecasting. Vendors of microgrid controllers and grid optimisation software are beginning to integrate forecasting into their products.

Because clouds typically have more local variation than wind, NWP models are being upgraded to provide the higher spatial resolution needed for PV forecasting. However, clouds are currently quite difficult to predict using NWP and cause very fast PV power ramps. Nevertheless, the *risk* of clouds can be predicted accurately, allowing more efficient scheduling of contingency reserves.

Smart Inverters

RE sources have several drawbacks from an electricity grid operator's point of view. They can cause transient grid voltage fluctuations ("flicker"), steady-state grid voltage problems and frequency deviations. However, when smart inverters are used to interface RE sources with the electric grid, these problems can be mitigated (Casey, *et al.*, 2010). In some cases, renewable sources employing smart inverters can even improve grid power quality beyond what it would be in the absence of renewables through for example, providing reactive power when the grid needs it.

Smart inverters can provide five specific functions that can help electricity systems operate more reliably and efficiently: volt-VAR control, voltage and frequency event ride-through, grid monitoring, high-frequency power reduction, and ramp-rate control.

Volt/Volt-Ampere Reactive Control

Inverters are electronic devices that connect most RE sources and energy storage devices with the electric grid, including PV, wind turbines and battery systems. Early inverters were designed to inject only real power (no reactive power) onto the grid. This causes the grid voltage to rise whenever RE output is high and to fall when RE output drops. This problem is easily fixed by employing inverters capable of providing reactive power (VARs) to regulate the grid voltage at their point of connection. Injection of VARs to control voltage is called volt-VAR control.

The simplest method of regulating voltage by injecting VARs requires no communication; the inverter is programmed so that its reactive power output is a function of the grid voltage at the inverter's point of connection. Alternatively, a communication link can enable inverters to output reactive power at the command of the grid operator (or the DA system). It may be simpler to stabilise grid voltage if control is centralised so that various distributed control schemes on a single line do not conflict.

Local provision of reactive power reduces power transmission losses and improves power quality. It can also save utilities money by avoiding the need for other forms of distributed voltage control.

Provision of volt-VAR control requires a minor reduction in maximum real power output. Slight over-sizing of inverter components eliminates this drawback (Zuercher-Martinson, 2011). Providing volt-VAR control does impose more stress on inverter components, potentially leading to early failure, although smart inverter manufacturers typically provide at least five-year standard warranties, with optional longer warranties, just as for non-smart inverters. Inverters capable of volt-VAR control cost only slightly more than inverters that are not, because it is primarily a control upgrade. These relatively minor drawbacks can be offset by fairly compensating inverter owners for voltage regulation services, but economic structures to enable this do not exist in many areas, particularly in highly regulated electricity markets. Compensation of inverter owners for reactive power is especially important if inverters are to provide reactive power when the inverter would otherwise be turned off (such as at night, for solar inverters), because the inverters will experience significantly more thermal aging.

Voltage and Frequency Event Ride-Through

Other smart inverter functions include voltage event ride-through (low- and high-voltage ride-through) and frequency event ride-through (low- and high-frequency ride-through). For safety reasons, grid-tied inverters are usually required to not output current to the grid when it is down or when its voltage or frequency are out of their specified operating ranges. However, when the grid voltage or frequency is experiencing problems, loss of power from RE may make the problem worse. Voltage and frequency event ride-through are control technologies that allow inverters to stay online and support the grid during brief periods of frequency or voltage deviation. These functions are typically preprogrammed into inverters and performed without any need for communications with the grid operator.

Grid Monitoring

Inverters monitor grid voltage, frequency, current and phase angle at the point where they connect to the grid as part of their standard control systems. If a smart grid communication link is available, inverters can send this information to grid operators, increasing the granularity of grid measurements without the expense of additional sensors. This information can also be displayed to inform stakeholders of system output, to educate the public, or for marketing purposes.

High-Frequency Power Reduction

Wind and solar inverters can be programmed to curtail power when grid frequency is high, helping grid operators to bring the frequency back within range. This can be done by ceasing to export power completely when frequency reaches a specified limit, or it can be done gradually as frequency increases (following what is known as a droop characteristic), in effect providing frequency down-regulation (Nelson, 2011). As with volt-VAR control, this can be performed with or without communicating with the grid operator. One downside of high-frequency power reduction is that it temporarily reduces the output of the RE source. If implemented correctly, this opportunity cost is justified by improvements in grid power quality or reduced grid control effort. If the RE source is not utility-owned, its owner may need to be compensated for this service to make up for lost power output.

Ramp-Rate Control

Power output from renewable resources can ramp up and down very rapidly, causing difficulties for grid operators. Smart inverters can be controlled to limit the rates at which power ramps up. If very small amounts of supercapacitor energy storage are included within smart inverters, the rate at which their power ramps down can also be limited.

Current Status of Smart Inverters

All of the smart inverter functions mentioned previously can be implemented at modest additional cost relative to the cost of a conventional (non-smart) inverter[7]. The prevalence of each technology in a given region of the world often depends on government or industry regulations and standards, which have historically restricted them in some regions. In general smart inverters are not necessary when variable renewables provide a small portion of grid capacity, but they become beneficial as higher penetrations (around 15%) are reached on any section of the grid and they are essential at very high penetrations (around 30%), although specific penetration levels vary with location (Hoke et al., 2013). These technologies are available from most or all major manufacturers of central inverters (defined as inverters larger than about 100 kW). Smart inverters are becoming standard equipment; it is recommended that they be used even at low RE penetrations to avoid needing to upgrade as RE levels increase.

Volt-VAR control, low-voltage ride-through, high-voltage ride-through, low-frequency ride-through, and high-frequency power reduction are all becoming standard features in some locations, especially for larger central inverters. Because they do not require communications or other infrastructure investments, they can be implemented independently of other smart grid technologies. Inverter-based volt-VAR control can also be incorporated into centralised voltage optimisation schemes, avoiding the need for dedicated voltage control devices. The control algorithms to do this at the distribution level are in development and at the pilot-project stage.

When smart inverters with volt-VAR control are used, it is generally not necessary to install additional non-RE-based voltage control devices to accommodate RE, although voltage control devices may be needed for other reasons.

Some electric utilities are reluctant to allow inverters (which are often not owned by the utility) to assist with voltage and frequency regulation, which conventionally are considered the utility's responsibility. As higher penetrations of RE have been installed in some areas, it becomes difficult for utilities to provide high-quality power without the assistance of renewable generators. In general, utilities are becoming more accepting of smart inverters and have even begun to require them in many cases.

There is a risk that large-scale provision of voltage and frequency regulation from distributed resources, if not implemented carefully, could contribute to serious problems, including grid instability and unintentional islanding during grid outages. These potential problems can be addressed through detailed interconnection studies, use of products certified by testing organisations and implementation of well-designed anti-islanding technology.

Distributed Storage

Electricity storage is extremely useful for adding flexibility to electric grids because it helps to deal with the variability and unpredictability of renewables. Electricity storage can be divided into *bulk storage*, which can output large amounts of power (multiple megawatts) over long periods of time (hours), and *distributed storage* that can output smaller amounts of energy (kilowatts to megawatts) over shorter periods of time (milliseconds to minutes).

Some of the technologies used (or proposed for use) in distributed storage include lithium-ion batteries, lead acid batteries, some types of flow batteries, thermal storage, flywheels, supercapacitors, and hydrogen storage. These technologies and others are summarised in a May 2012 IRENA report entitled *Electricity Storage and Renewables for Island Power* (IRENA, 2012) and in a technology policy brief by IRENA and the International Energy Agency's Energy Technology Systems Analysis Programme (IEA-ETSAP and IRENA, 2012). This section focuses on the use of distributed storage to facilitate integration of renewable resources into the electric grid.

---

[7] *The technology to control the rate at which inverter power ramps down is in development and is expected to add moderately to the cost of the inverter.*

Bulk storage is mentioned briefly in the section on bulk power technologies.

Distributed storage is largely still in a research and pilot project phase. Technologies are available, and some of them are reliable, but costs are still too high to allow for widespread deployment in larger electricity grids at a commercial level. However, costs are coming down, storage solutions are being integrated by renewable power suppliers at a household and commercial level, and distributed storage may play a significant role in the future electric grid.

Individual distributed energy storage plants generally do not have sufficient capacity to store large amounts of RE (many megawatt-hours) for use later in the day, which is the first thing that many people think of when RE and storage are mentioned together. Benefits that *can* be provided by distributed storage include:

- Grid frequency and voltage regulation (grid stabilisation and power quality control).
- Smoothing of renewable power variability (ramp-rate control).
- Small-scale energy arbitrage (especially with thermal storage[8]).
- Shaving of short-term load peaks.
- Shaving of short-term RE peaks.
- Backup power: short-term islanding of micro-grids and supplying loads briefly after islanding before distributed generation comes online (see the section on microgrids).
- Improvement of distribution system asset utilisation and deferment of distribution system upgrades.

Large aggregations of distributed storage would improve the ability to shift renewable power to times when it is needed; however, such aggregations are not expected to be available in the very near future due to high costs. One possible exception to this would be to take advantage of EV batteries for grid storage, as mentioned below.

The specific benefits of a given storage technology depend on its energy capacity and maximum input and output power. Supercapacitors and flywheels can only store a few seconds' or minutes' worth of energy at their rated power, but they can respond very quickly to power commands, making them more appropriate for very short-term ramp-rate control and frequency regulation. Supercapacitors could be included inside smart inverters for this purpose.

Complete life-cycle economics of storage projects should be considered when evaluating systems. The life expectancy of the storage medium is one important economic factor. Lead acid and lithium-ion batteries both have lifetimes in the five- to 10-year range in most applications, which is much shorter than most distribution system hardware. Hydrogen storage system life cycles can be even shorter. The round-trip conversion efficiency of the entire energy storage system should also be taken into account; typically, losses are at least 10% and often they are significantly higher.

Lithium-ion batteries are receiving the most attention currently in terms of research and pilot projects. High cost and low life expectancy are the major factors preventing wider deployment; both cost and lifetime are gradually improving. Lead acid batteries have been around the longest and are the most commercially mature and economical, with extensive use in off-grid power systems and grid backup systems.

ADR, as described in a previous section, can provide many of the same benefits as distributed storage (such as shifting load to align with renewable power) at a lower cost.

Distributed storage can be owned by the grid operator, a customer, or a third party. Customer-owned storage can be controlled by the customer's energy management system, controlled manually by the customer, or controlled by the utility (for example, through a DA system), although the latter option may not be acceptable to many customers. The benefits to the utility of customer-owned storage are better captured if storage is aggregated across many customers. Because storage can be used to provide seamless backup power, when high values are placed on reliability, customer-sited storage is economical even without capturing its other benefits.

In order for the benefits of distributed storage to be maximised, its control may need to be incorporated into DA systems, DR programmes, or advanced pricing schemes.

Distributed storage does not yet have strong regulatory support. Methods for measuring and compensating the benefits of storage to the electric grid are not well developed (Kaufman, *et al.* 2011, Bacher Energie, n.d.).

Electric Vehicles

If EVs, including plug-in hybrid electric vehicles, are deployed widely, their batteries could be used as distributed storage. This would require the vehicles to be able to discharge power back into the grid (known as vehicle to grid or V2G), a technology that is still in development,

---

[8] *Distributed thermal storage involves using off-peak electricity to cool or heat a medium (typically water). The cold or hot medium is then used when electricity prices are high.*

but which will not add significantly to the cost of an EV charger.

EVs with V2G capability could provide many of the benefits described above. Indeed, the economics of using EV batteries as distributed storage may be better than for dedicated storage devices because EV batteries would serve dual purposes.

Most proposals for the use of EVs as storage would aggregate many EVs so that they form a single resource from the grid operator's perspective. It has even been proposed that an aggregation of EVs could provide benefits typically only available from bulk storage, such as bulk energy arbitrage. However, given that batteries are already the weak spot in EVs, it is unlikely that this would be economical in the coming decades because of the significant additional wear when batteries are cycled deeply. On the other hand, moving small amounts of energy into and out of lithium-ion batteries causes much less wear than cycling them deeply, so it is possible that benefits associated with distributed storage could be economically provided by EVs. Early research on this is under way.

Currently available EVs do not include V2G capability. However, EV batteries can be used as smart loads even without V2G. By intelligently controlling the charging of an EV (or group of EVs), services such as ramp-smoothing, voltage control, and frequency regulation can be provided while charging. In fact, because EVs typically charge at night, they are well suited to absorb power from wind generation, which often peaks at night. Grid-friendly EV charging can be encouraged by advanced electricity pricing. Most EV charging is not currently done in a grid-friendly manner; in fact, EVs are a small but growing burden on the grid, but this situation can be turned around by smart charging. In order for EV owners to be fairly compensated for the benefits of smart charging, new business processes will need to be developed, and a system to recognise individual EVs—regardless of where they plug in—will need to be implemented.

Microgrids and Virtual Power Plants

Microgrids and VPPs are two approaches to aggregating grid resources to achieve particular goals. Because a VPP or microgrid can be large enough to access the wholesale electricity market, it can pass real-time wholesale pricing signals to its internal sources, loads and storage, leading to more efficient price signal response.

Microgrids

A microgrid is a section of an electric grid that can disconnect from the main grid and operate autonomously, supplying its own loads from internal power sources for some period of time. Microgrids are typically on the scale of a small town, neighbourhood, military base, or university or commercial campus. Some definitions of the term microgrid include power systems that are never connected to a central power grid. A typical microgrid includes:

- An intelligent microgrid switch to handle connection and disconnection from the central grid.
- Internal energy sources (often including energy storage).
- A microgrid controller to control and optimise microgrid resources.

When a microgrid is operating without a connection to the central power grid, it is said to be "islanded." A microgrid may island itself from the central grid during a grid outage or when grid power quality is poor, providing improved reliability and power quality to loads within the microgrid. This ability also allows renewable resources within the microgrid to continue operating even during grid outages. The ability to operate in islanded mode may be especially beneficial in countries where power quality and grid reliability are low. A microgrid will almost definitely require energy storage if it is designed to transition into island mode without temporary loss of power to internal loads when the central grid experiences an unplanned outage.

In microgrids the presence of local power sources and the ability to regulate voltage and frequency can alleviate some of the utility's burden. If renewable sources are included within a microgrid, their variability can be managed by the microgrid, preventing the utility from needing to deal with it.

A microgrid is controlled by a supervisory controller that decides which microgrid energy resources to use at what times in order to balance load and generation. This microgrid controller may take into account predicted load profile, predicted power price profile, predicted wind or solar power profile, predicted heating or cooling needs (if the microgrid contains cogeneration), emissions and other parameters. The microgrid controller may also change the operating modes of power resources, provide power setpoints to resources, or regulate droop characteristics.

A microgrid switch (the switch that performs the islanding and connection functions) also has an intelligent controller.

Simple microgrids containing one or two diesel or natural gas generators are fairly common in locations where reliability is valued highly—such as at hospitals, military installations, and some factories—although historically, these installations were not referred to as microgrids. Implementations of the modern concept of more complex microgrids that contain diverse power sources that are controlled for purposes beyond reliability are much less common.

Microgrid technology is undergoing significant research and development, and several more complex pilot projects are under way. (See, for example, Takada, 2011). One source reports that typical utility distribution microgrids cost around USD5 per watt of capacity (Pullins and Asmus, 2012). In areas with reliable power grids, microgrids are not typically justified economically at present, unless reliability is valued highly. In areas with less reliable power systems, microgrids may be more easily justified economically.

Virtual Power Plants

A VPP is similar to a microgrid in that it is an aggregation of energy resources that can be treated as a single larger resource from the grid operator's perspective, but different in that the resources may not be geographically co-located and generally do not have the ability to operate independently from the grid[9]. Specific definitions of VPP vary. In general a VPP may use any combination of renewable power sources, conventional power sources, energy storage and DR. A central controller or aggregator coordinates the resources so that they can be treated as a single resource from the grid operator's perspective.

Because a VPP does not need special hardware or intelligent switchgear and can draw from resources distributed throughout a power grid, a VPP is typically less expensive to implement than a microgrid. In fact, because VPPs are tied together by software controls, a given VPP may last for only a short length of time (a year, a month, or less than a day) and can be easily and inexpensively modified.

An aggregation of DR resources configured to be reliable and dispatchable can form a virtual peaking power plant without adding any actual generation. This type of VPP has been piloted in the U.S. Energy prices based on real-time bulk electricity generation costs are rarely transmitted to customers, but VPP operators can access wholesale prices and pass them on to DR and other resources without direct involvement from grid operators. This allows more efficient use of grid resources without complicating utility operations.

An aggregation of renewable resources can also act as VPP, as has been piloted in Europe[10]. When geographically and technologically diverse renewable resources are grouped together, the reliability of the group is significantly higher—and the variability significantly lower—than that of each individual resource due to aggregation effects. Even if a group contains no dispatchable resources, it may still be useful to consider it a VPP, albeit one that must be treated differently from a conventional power plant. There are advantages from the utility's perspective in dealing with a single, less variable VPP over dealing with myriad highly variable individual sources. The addition of dispatchable DR resources to a renewable VPP can result in a large, reliable VPP that uses no fossil fuel-based power sources and no costly energy storage.

Because the resources that make up VPPs may be far apart, a VPP's operation depends on reliable transmission infrastructure and compatible regulations. These prerequisites may not be present in many areas. Where they are present, VPPs are expected to be valuable and low-cost tools for grid management. However, regulations relating to VPPs are varied and inconsistent, and standards are lacking.

Bulk Power Technologies

Most of the smart grid technologies reviewed in this document are applied at the power distribution level[11]. This section briefly reviews a few renewable-friendly smart grid technologies that are applied at the bulk power generation and transmission level. The technologies are listed in order of decreasing technological maturity. Table 5C summarises several characteristics of the technologies described here, using colour coding where applicable to give a general indication of whether a particular characteristic reflects positively, neutrally, or negatively on each technology. These ratings are general guidelines only and will vary widely with system details.

Flexible AC Transmission Systems

Flexible AC transmission systems (FACTS) are a family of devices that use power transistor devices to regulate grid voltage or power factor, improving dynamic grid stability and power quality (ABB, n.d.). Two more com-

---

[9] *A microgrid could be considered a type or subset of VPP that is able to operate in island mode and is geographically co-located.*

[10] *See for example, http://fenix-project.org/.*

[11] *One exception is renewable forecasting, which is typically applied to bulk generation, but is expected to be useful for distributed generation in the future. In addition, smart inverters are used in PV plants connected at both the transmission and the distribution levels.*

Table 5C: Smart grid technologies for bulk power

Technology	Maturity	Availability / Market penetration	Economics	Risks/ Disadvantages	Problems mitigated	Time scale
Flexible AC transmission systems (FACTS)	Mature	Commercial, relatively common	Often much more economical than alternatives such as line upgrades	May not be necessary for RE support as inverter-based volt-VAR control is adopted	Voltage issues due to old wind tech, non-smart inverters, and other causes	Sub-sec and above
Direct current (DC) links, including HVDC transmission	Mature	Commercial, relatively common	HVDC cost lower than AC for distance > 1,000 km	High cost of each connection point	Long-distance transmission losses; underwater transmission; connection of asynchronous grids	All
Bulk storage	Pumped stored hydropower (PSH) mature; others demo, R&D	PSH commercial, common; others uncommon	PSH: high capital cost but good long-term benefits; others not yet economical	Geography dependent; high capital cost	Hourly and daily load following; time-shifting of RE; real and reactive power regulation	Min, hr, days
Dynamic line ratings (DLR)	Demo	Commercially available, uncommon	Expected to be cost-effective on frequently congested lines	Some market structures disincentivise DLR unnecessarily	Insufficient transmission capacity; wind power curtailment	Min, hr
Synchrophasors (PMUs)	R&D, demo	Early commercial, uncommon	USD 2000–3000 per location plus communications and data processing; not fully known	Young technology	Lack of real-time T&D monitoring; need for dynamic control of T&D	Sub-sec, sec, min

Key: Colors indicate qualitative rating of each technology:

Generally positive, at least in some cases

Generally neutral

Generally negative

monly used members of the FACTS family are static VAR compensators (SVCs) and static synchronous compensators (STATCOMs) (Noroozian, 2003).

SVCs use thyristor switches to shunt grid current through capacitors (or sometimes inductors), supplying (or consuming) reactive power to adjust the grid voltage and power factor (ABB, 2011). SVC technology has been available since the 1950s and has gradually been replacing synchronous condensers, which are rotating machines previously used to provide reactive power. STATCOMs serve the same purpose, but use voltage-sourced inverters to shunt current. STATCOM technology is newer, faster and more expensive than SVC technology. Both devices have the effect of increasing transmission line capacity by providing reactive power locally and are widely available commercially. FACTS are sometimes used in conjunction with large wind plants, especially with older turbine technologies.

As noted in a previous section, smart inverters can also provide reactive power to control voltage and power factor. In fact, a STATCOM is basically a smart inverter without a power source (so it can only supply reactive power). Where smart inverters are used, wind and solar plants will not require utilities to install FACTS (although FACTS may still be needed for other non-RE-related reasons).

Direct Current Links

Electric power is typically transmitted as alternating current (AC). Modern power electronics allow AC to be efficiently converted into direct current (DC). Utilities are beginning to use some high-voltage DC (HVDC) transmission. HVDC lines themselves are less expensive and have lower losses, but the AC-DC converters at each end are costly, so conversion to HVDC only makes economic sense in specific scenarios (Hingorani, 1996), primarily these:

- *Long distances:* For very long point-to-point transmission applications (more than 500 kilometres to 1,000 kilometres), HVDC lines are more economical because the high cost of the converter stations at each end is outweighed by decreased transmission losses and the lower cost of conductors (Bahrman, 2006). Note that electricity cannot be accessed midway along an HVDC line without adding another costly conversion station.
- *Underwater:* AC electric lines experience more losses when run underwater due to capacitance between the lines and the water and protective metal enclosures. DC transmission lines do not have this disadvantage and hence are often used to conduct power underwater.
- *Connection of separate AC grids:* Two separate AC grids cannot share AC power even if they have the same nominal frequency, due to differences in phase and minor differences in frequency. DC ties allow power to pass between unsynchronised AC electric grids. The DC tie also helps prevent instability in one grid from affecting the other grid. The direction and amount of power flowing through a DC line can be controlled precisely.

Bulk Storage

Bulk (long-term) energy storage, when available, is extremely useful for storing renewable electricity for use at later times. In general, bulk storage is used to store electricity at off-peak times and release it during peak times, sometimes called energy arbitrage. It can be used for ancillary services including frequency regulation, load following, and voltage regulation. The operational flexibility afforded by storage also facilitates optimisation of grid asset utilisation and deferral of upgrades to transmission and distribution infrastructure.

Two recent reports provided more detailed summaries of electricity storage methods than are given here (IRENA, 2012 and IEA-ETSAP, 2102). Pumped stored hydropower accounts for more than 99% of currently installed storage capacity worldwide (Economist, 2012). Water is pumped uphill to store energy and released through a turbine to generate electric power. It is a well-proven technology, although capital costs are still significant. The need to store vast amounts of water in two reservoirs close together, with one reservoir hundreds of metres above the other, limits pumped stored hydropower to areas with convenient geography. Another form of bulk storage that also takes advantage of geography is compressed air energy storage. This involves pumping air into an enclosure (often underground) and releasing it to spin a turbine. This technology is not new, but only a small number of installations exist worldwide.

Several newer forms of bulk energy storage are being piloted. These include sodium sulphur batteries, flow batteries (including zinc bromide and vanadium redox) and molten salt thermal energy storage, which is convenient for use with concentrated solar thermal power. All of these are in the pilot project stage. Lithium-ion batteries are also beginning to target long-term storage in demonstration projects. These technologies are capital-intensive and are not yet cost-effective without subsidy, although the technologies are improving and prices are approaching levels that will make storage cost-effective. Bulk storage will first become cost-effective in areas with expensive electricity and large differentials between maximum and minimum electricity prices. Storage may also be beneficial in remote or island locations where expensive diesel generators can be made to run more efficiently (IRENA, 2012).

As with distributed storage, bulk storage is at a disadvantage in most areas because markets and regulations are not configured to value some of its benefits, such as ancillary services and deferment of generation and transmission upgrades.

Dynamic Line Ratings

The capacity of power lines to carry current (in air) decreases with increased conductor temperature; in turn, conductor temperature increases with ambient temperature and solar radiation, and decreases with wind speed. Traditionally, power lines are given a single power rating based on the worst case weather scenario, meaning that they are almost always underutilised. Dynamic line rating (DLR) technology actively senses transmission line tension, which is directly related to the average temperature on the line. This allows real-time line rating values to be incorporated into transmission grid operations (Smartgrid.gov, n.d.). The result is that line capacity increases by at least 10% over 90% of the time, and by up to 40% at some times (Aivaliotis, 2010).

DLR is especially advantageous in conjunction with wind power, because wind cools lines, increasing their capacity. Line congestion, which frequently leads to unwanted wind curtailment in many regions, can be alleviated by DLR without the need for expensive and time-consuming line upgrades. DLR also gives grid operators valuable real-time knowledge of transmission line power flows, which are not always available.

Though DLR technology is not new, it is only now being used in pilot projects (Johnson, 2010). It is expected to be cost-effective on lines that are frequently congested.

However, current market structures in some areas are not set up to incentivise investment in DLR.

Synchrophasors

Synchrophasors, also known as phasor measurement units (PMUs) are devices that measure the magnitude and phase of transmission line current and voltage 25 times per second to 120 times per second. A time reference provided by a global positioning system (GPS) is used to synchronise measurements from all the PMUs in a system to provide an accurate, near-real-time picture of an entire transmission system.

PMU measurements are aggregated by a phasor data concentrator and relayed to the grid control system, facilitating advanced grid control and optimisation methods (including the use of DLR). PMUs are an improvement over current grid-monitoring technology, which gives a picture of the grid that is at least five minutes old (and sometimes much older) by the time it arrives at the control centre. PMU systems are expected be installed at wind plants in the future and the wide-area situational awareness provided by PMU systems is expected to facilitate integration of variable RE sources.

Each PMU costs USD 2,000 to USD 3,000; communications and data processing systems make total projects much more expensive. Exact costs of synchrophasor data processing systems are not known because the technology is still in development. Synchrophasor systems can enable higher RE penetrations without requiring transmission system upgrades. Brazil and Mexico were early adopters of PMU technology, and China may now be the world leader in installations. PMU communications systems and data models lack standardisation. Research and development of synchrophasor technology is rapidly ongoing.

List of Abbreviations

AC	Alternating Current
ADR	Automated Demand Response
AMI	Advanced Metering Infrastructure
AMR	Automatic Meter Reading
BEMS	Building Energy Management System
BPL:	Broadband Over Powerline
CAES	Compressed Air Energy Storage
CEN	European Committee for Standardization
CENELEC	European Committee for Electrotechnical Standardization
ETSI	European Telecommunications Standards Institute
CHP	Combined Heat and Power
CPP	Critical Peak Pricing
CVR	Conservation Voltage Reduction
DA	Distribution Automation
DC	Direct Current
DLC	Direct Load Control
DLR	Dynamic Line Rating
DR	Demand Response
DSM	Demand Side Management
EV/s	Electric Vehicle/s
FACTS	Flexible Alternating Current Transmission System
FLISR	Fault Location, Isolation and System Restoration
GPS	Global Positioning System
GW	Gigawatt
HEMS	Home Energy Management System
HFRT	High-Frequency Ride-Through
HVDC	High Voltage Direct Current
HVRT	High-Voltage Ride-Through
IEA	International Energy Agency
IEEE	Institute of Electrical and Electronics Engineers
IRENA	International Renewable Energy Agency
ISO	Independent System Operator
IVVC	Integrated Volt-VAR Control
kW	Kilowatt
kWh	Kilowatt-hour
kWp	Kilowatt peak
LFRT	Low Frequency Ride-Through
Li-ion	Lithium –ion
LIDAR	Light Detection and Ranging
LVRT	Low Voltage Ride-Through
NWP	Numerical Weather Prediction
O&M	Operations and Maintenance
PDC	Phasor Data Concentrator
PHEV	Plug-in Hybrid Electric Vehicle
PLC	Power Line Carrier
PMU	Phasor Measurement Unit
PSH	Pumped Stored Hydropower
PV	Photovoltaic
RE	Renewable Energy
RTP	Real-Time Pricing
SAIDI	System Average Interruption Duration Index
SCADA	Supervisory Control and Data Acquisition
SODAR	Sonic Detection and Ranging
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
T&D	Transmission and Distribution
TCP/IP	Transmission Control Protocol / Internet Protocol
TOU	Time-Of-Use
U.S.	United States
V2G	Vehicle to Grid
VAR	Volt-Ampere Reactive
VPP	Virtual Power Plant

References

ABB (n.d.), "Dynamic Shunt Compensation", *www.abb.com/industries/us/9AAC30200111.aspx*, accessed November 2012.

ABB (2011), "SVC: A Cost and Time Effective Option to a 330 kV Grid Expansion", *www05.abb.com/global/scot/scot221.nsf/veritydisplay/793bfb6d691ddf0bc125781f0027d91f/$file a02-0223%20e%20lr.pdf*. Accessed November 2012.

Ahlstrom, M. and A. Kankiewicz (2009), "Solar Power Forecasting, Perspective and Understanding on Solar Power Forecasting", Utility-Scale PV Variability Workshop, WindLogics, *www.uwig.org/pvwork/7-Ahlstrom.pdf*. Accessed November 2012.

Aivaliotis, S.K. (2010), "Dynamic Line Ratings for Optimal and Reliable Power Flow", The Valley Group, FERC (Federal Energy Regulatory Commission) Technical Conference, June 2010.

Asmus, P. (2010), "Will New Technologies Boost Wind Forecasting Accuracy?", Pike Research, July 2010.

Autoridad de Energia Electrica de Puerto Rico (2011), "Plan Tactico para Optimizar las Operaciones y Servicios", March 2011, *www.aeepr.com/DOCS/PREPA%20Smart%20Grid%20Roadmap%20Espa%C3%B1ol.pdf*. Accessed November 2012.

Autoridad de Energia Electrica de Puerto Rico (2012), "Proyecto de Energia Renovable", *www.aeepr.com/proyectos_ener_renv3.asp,* accessed October 2012.

Bacher Energie (n.d.), "DG System Integration in Distribution Networks; The transition from passive to active grids", presentation, *http://tinyurl.com/97mmuwr*, accessed October 2012.

Baer, W.S., B. Fulton and S. Mahnovski (2004) "Estimating the Benefits of the GridWise Initiative", Phase I Report, Rand Science and Technology Technical Report, Prepared for the Pacific Northwest National Laboratory, *www.rand.org/pubs/technical_reports/2005/RAND_TR160.pdf*. Accessed November 2012.

Bahrman, M. (2006), "HVDC Transmission", IEEE (Institute of Electrical and Electronics Engineers) Power Systems Conference and Exposition, November 2006.

Bliek, F., A. van den Noort, B. Roossien, R. Kamphuis, J. de Wit, J. van der Velde and M. Eijelaar (2010), "PowerMatching City, a Living Lab Smart Grid Demonstration", presentation at Innovative Smart Grid Technologies Conference Europe (ISGT Europe), *www.kema.com/Images/IEEEPMC.pdf*. Accessed November 2012.

Breslin, M. (2009), "The Colorado-Denmark Connection: Energinet.dk Finds Colorado Partners to Help Manage Distributed Generation", Intelligent Utility Magazine, January 2009, *www.intelligentutility.com/magazine/article/107476/colorado-denmark-connection*. Accessed November 2012.

Burger, A. (2012), "Puerto Rico Solar Power Plant Built to Withstand Hurricanes, Deliver Power Reliably in All Types of Weather", CleanTechnica, October, *http://cleantechnica.com/2012/10/03/puerto-rico-solar-power-plant-built-to-withstand-hurricanes-deliver-power-reliably-in-all-types-of-weather/*. Accessed November 2012.

Carson, P. (2011), "Solar Forecasting and Microgrids: It's All About Balance on the 'Island' ", Intelligent Utility Magazine, October 2011, *www.intelligentutility.com/article/11/10/solar-forecasting-and-microgrids*. Accessed November 2012.

Casey, L.F., *et al.* (2010), "Advanced Inverters Facilitate High Penetration of Renewable Generation on Medium Voltage Feeders—Impact and Benefits for the Utility", IEEE (Institute of Electrical and Electronics Engineers) Conference on Innovative Technologies for an Efficient and Reliable Electricity Supply (CITRES), September.

CEN (European Committee for Standardization) (2012), "Joint CEN, CENELEC and ETSI Activity on Standards for Smart Grid", *www.cen.eu/cen/Sectors/Sectors/UtilitiesAndEnergy/SmartGrids/Pages/default.aspx*. Accessed November 2012.

Chan, M., *et al.* (2012), "Preliminary AMI Deployment Costs from the U.S. DOE Smart Grid Investment Grant Program", United States Association for Energy Economics Dialogue, Vol. 20, No. 1, *http://dialogue.usaee.org*. Accessed November 2012.

Clean Energy Prospector (2012), "Skyprospector Project Funded by the TSB (Technology Strategy Board)", *www.cleanenergyprospector.com/2012/04/skypros-*

pector-project-funded-by-the-tsb/. Accessed November 2012.

CNN Money (2012), "Wind Power Hits 57% Mark in Colorado", August 6, *http://money.cnn.com/2012/08/06/news/economy/wind-power-Colorado/index.htm*. Accessed November 2012.

Colorado Smart Grid Task Force (2011), "Deploying Smart Grid in Colorado: Recommendations and Options", final report, *www.merid.org/en/Content/Projects/Colorado_Smart_Grid_Task_Force.aspx?view=docs*. Accessed November 2012.

Cordero, M. (2010), "Puerto Rico Electric Power Authority—Company Overview and Project Development", Puerto Rico Credit Conference 2010, February2010.

Cornish, K. and E. Shepard (2009), "Societal, Environmental Benefits in the Smart Meter and Smart Grid Business Case", Power Grid International, December 2009.

Danish Energy Agency (2012), "Månedlig elforsyningsstatistik", HTML spreadsheet summary tab B58-B72 18, January2012, *www.ens.dk/da-DK/Info/TalOgKort/Statistik_og_noegletal/Maanedsstatistik/Documents/El-maanedsstatistik.xls*. Accessed November 2012.

Danish Energy Association (n.d.), "Statistics", *www.danishenergyassociation.com/Statistics.aspx,* accessed November 2012.

Doris, E. and K. Peterson (2011), "Government Program Briefing: Smart Metering", National Renewable Energy Laboratory, September2011.

Economist, The (2012), "Energy Storage: Packing Some Power", March 3, *www.economist.com/node/21548495*. Accessed November 2012.

EPRI (Electric Power Research Institute) (2011), "Estimating the Costs and Benefits of the Smart Grid", March 2011.

Energinet.dk (2010), "Smart Grid in Denmark", *www.energinet.dk/SiteCollectionDocuments/Engelske%20dokumenter/Forskning/Smart%20Grid%20in%20Denmark.pdf*. Accessed November 2012.

ENISA (European Network and Information Security Agency) (2012), "Smart Grid Security: Recommendations for Europe and Member States", *www.enisa.europa.eu*. Accessed November 2012.

European Climate Foundation (2011), "Power Perspectives 2030", *www.roadmap2050.eu*. Accessed November 2012.

European Commission (2012a), "Commission Recommendation of 9 March 2012 on Preparations for the Roll-out of Smart Metering Systems", *http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2012:073:0009:0022:EN:PDF.* Accessed November 2012.

European Commission (2012b), Joint Research Centre, "Smart Grid Cost-Benefit Analysis", *http://ses.jrc.ec.europa.eu/smart-grid-cost-benefi -analysis*. Accessed November 2012.

Faruqui, A. (2010), "Dynamic Pricing & Customer Behavior", Fourth Annual Electricity Conference, March, *www.ece.cmu.edu/~electricityconference/2010/Faruqui_Dynamic pricing and customer behavior (03-08-10).pdf*. Accessed November 2012.

Faruqui, A. (2012), "From Smart Metering to Smart Pricing", Brattle Group, *www.brattle.com/_documents/uploadlibrary/articlereport2439.pdf*. Accessed November 2012.

FERC (Federal Energy Regulatory Commission) (2011), "2010 Assessment of Demand Response and Advanced Metering". http://www.ferc.gov/legal/staff-reports/2010-dr-report.pdf. Accessed May 2013.

Giordano, V., *et al.* (2012), "Guidelines for Conducting a Cost-Benefit Analysis of Smart Grid Projects", European Commission – Joint Research Centre, *http://ec.europa.eu/energy/gas_electricity/smartgrids/doc/20120427_smartgrids_guideline.pdf*. Accessed November 2012.

Glassmire, J., P. Komor and P. Lilienthal (2012), "Electricity Demand Savings from Distributed Solar Photovoltaics", *Energy Policy,* Vol. 51, issue C, pp. 323-331.

Gross, D. (2010), "Spotlight on Singapore: Smart Grid City", Cleantech, *www.cleantechinvestor.com/portal/smart-grid/5860-spotlight-on-singapore-smart-grid-city.html*. Accessed November 2012.

Hand, M., S. Baldwin, E. DeMeo, J.M. Reilly, T. Mai, D. Arent, G. Porro, M. Meshek, and D. Sandor (2012), "Renewable Electricity Futures Study", National Renewable Energy Laboratory, NREL/TP-6A20-52409, *www.nrel.gov/analysis/re_futures/*. Accessed November 2012.

Hedrick, K. (2012), "Demand Side Management: Why utility-directed load management programs make more sense than ever before", Landis+Gyr, pp. 5.

Hingorani, N.G. (1996), "High-Voltage DC Transmission: A Power Electronics Workhorse", *IEEE Spectrum*, April 1996.

Hoke, A. and P. Komor (2012), "Maximizing the Benefits of Distributed Photovoltaics", *The Electricity Journal*, April 2012, Vol. 25, No. 3.

Hoke, A. (2013), R. Butler, J. Hambrick, and B. Kroposki, "Steady-State Analysis of Maximum Photovoltaic Penetration Levels on Typical Distribution Feeders," *IEEE Transactions on Sustainable Energy*, April 2013.IEEE (Institute of Electrical and Electronics Engineers)/PES (Power and Energy Society) (2007/2008), Distribution Automation Tutorial, *http://wiki.powerdistributionresearch.com/index.php?title=IEEE/PES_Distribution_Automation_Tutorial_2007/2008*. Accessed November 2012.

IPCC (Intergovernmental Panel on Climate Change) (2012), "Renewable Energy Sources and Climate Change Mitigation", Special Report of the IPCC, Cambridge University Press, Cambridge.

IEA (International Energy Agency) (2012), "Energy Technology Perspectives 2012", *www.iea.org*. Accessed November 2012.

IEA-ETSAP (International Energy Agency-Energy Technology Systems Analysis Programme) and IRENA (International Renewable Energy Agency) (2012), "Electricity Storage Technology Brief", April 2012.

IRENA (2012), "Electricity Storage and Renewables for Island Power", May 2012, *www.IRENA.org*. Accessed November 2012.

Johnson, J. (2010), "Smart Grid Demonstration Project—Dynamic Line Rating (DLR)", Oncor Electric Delivery Company, June 2010.

Kaufman, S., P. Komor, B. Langdon and P. Vallett (2011), "Electricity Storage in Regulated Markets: Getting the Rules Right", *The Electricity Journal*, Vol. 24, Issue 6, pp. 63–71.

King, C. (2005), "Advanced Metering Infrastructure (AMI)", DRAM Coalition, *www.oregon.gov/PUC/electric_gas/010605/king.pdf?ga=t*. Accessed November 2012.

King, C. (2012), "Building a Business Case for Smart Meters", *www.emeter.com/smart-grid-watch/2012/building-a-business-case-for-smart-meters/*. Accessed November 2012.

Kroposki, B. (2011) "SunShot Initiative High Penetration Solar Portal: Ask an Expert," https://solarhighpen.energy.gov/ask/what_definition_high_penetration. Accessed May 2013.

Leeds, D.J. (2009), "The Smart Grid in 2010: Market Segments, Applications and Industry Players", Greentech Media Research, July 2009.

Levin, R. (2012), "Time-Variant Pricing: Time-of-Use vs. Critical Peak Pricing", California Public Utilities Commission, June 2012.

Lew, D., M. Milligan, G. Jordan and R. Piwko (2011), "The Value of Wind Power Forecasting", 91st American Meteorological Society Annual Meeting, the Second Conference on Weather, Climate, and the New Energy Economy, January 2011.

Madrigal, A. (2010), "Laser Guidance Adds Power to Wind Turbines", Wired, *www.wired.com/wiredscience/2010/03/lidar-wind/*. Accessed November 2012.

Martinez, M.S. (2004), "Delivering Cost-Effective Demand Response: A Portfolio Approach", Southern California Edison, September 2004.

McGregor, T., *et al*. (2012), "Realizing the Value of an Optimized Electric Grid", Gridwise Alliance, *www.gridwise.org/uploads/downloads/GridWiseAlliance_RealizingValueofOptimizedGrid_2_2012.pdf*. Accessed November 2012.

Menon, A (2011), "Smart Grid Technologies for Sustainable Cities: Implementation potential in ASEAN", Institute for Infocomm Research Singapore, *http://smartgrid.i2r.a-star.edu.sg/2012/slides/siemens.pdf*. Accessed November 2012.

MetaVu (2011), "SmartGridCity™ Demonstration Project Evaluation Summary", pp. 128, Meta Vu, Denver.

MIT (Massachusetts Institute of Technology) (2011), "The Future of the Electric Grid", *http://mitei.mit.edu/publications/reports-studies/future-electric-grid*. Accessed November 2012.

NETL (National Energy Technology Laboratory) (2009), "Building a Smart Grid Business Case", August 2009, *www.netl.doe.gov/smartgrid/referenceshelf/whitepapers/Whitepaper_Building%20A%20Smart%20Grid%20Business%20Case_APPROVED_2009.pdf*. Accessed November 2012.

NIST (National Institute for Standards and Technology) (n.d.), "Smart Grid Website", www.nist.gov/smartgrid/, accessed November 2012.

Nelson, R. (2011), "Active Power Control in Siemens Wind Turbines", Siemens Energy.

New Mexico Green Grid (n.d.), "Mesa Del Sol Smart Grid Project: High Penetration PV Feeder Grid Demonstration", *http://newmexicosmartgrid.com/files/mesadel-sol-onepage-projectflyer.pdf,* accessed October 2012.

Northeast Group, LLC (2012), "Middle East & North Africa Smart Grid: Market Forecast (2012-2022)".

Noroozian, M., *et al*. (2003), "Benefits of SVC and STATCOM for Electric Utility Application", IEEE Transmission and Distribution Conference and Exposition.

Perez, R. and T.E. Hoff (2008), "Energy and Capacity Valuation of Photovoltaic Power Generation in New York", Clean Power Research for the Solar Alliance and the New York Solar Energy Industry Association, pp. 18.

Postelwait, J. (2011), "Solar Forecasting—Next Big Thing in Sun-based Power?", Electric Light and Power, *www.elp.com/index/display/article-display/1879061058/articles/electric-light-power/volume-89/issue-5/sections/wolar-forecasting-next-big-thing-in-sun-based-power.html*. Accessed November 2012.

Power Partners (n.d.), "Resource Guide", *www.uspowerpartners.org/Topics/SECTION4Topic-ElecDistribution.htm*, accessed October 2012.

Puerto Rico Electric Power Authority (2011), "Minimum Technical Requirements for Photovoltaic Generation (PV) Projects", *www.fpsadvisorygroup.com/rso_request_for_quals/PREPA_Appendix_E_PV_Minimum_Technical_Requirements.pdf*. Accessed November 2012.

Pullins, S. and P. Asmus (2012), "Utility Distribution Microgrids", Pike Research webinar, September 2012.

Romero Barcelo, C. (2012), "Can Puerto Rico Find a Solution to Its Unacceptably High Energy Costs?", *Caribbean Business*, May 2012.

Rudden, R. and K. Rudden (2012), "The Value of Sustainability: At Least $20-25 Billion for Utility Investors", Target Rock Advisors Research Note, *www.targetrockadvisors.com/dox/reports/Target%20Rock%20Value%20of%20Sustainability%20Research%20Note%20%2805-23-12%29.pdf*. Accessed November 2012.

SDG&E (San Diego Gas & Electric Company) (2011), "SDG&E Smart Grid Deployment Plan: 2011–2020", California Public Utilities Commission Filing, June 2011, *www.sdge.com/sites/default/files/documents/smartgriddeploymentplan.pdf*. Accessed November 2012.

Sandlin, D. (2009), "Rate Design to Complement AMI Implementation in Danville, Virginia", Danville Utilities, September 2009.

Shimizu Corporation (2012), "Nine Japanese Companies Launch Japan-U.S. Collaborative Smart Grid Demonstration Project in Business District of Albuquerque, New Mexico", Press Release: dated May 18, 2012, *www.shimz.co.jp/english/news_release/2012/2012005.html#note1*. Accessed November 2012.

Singapore Energy Market Authority (2012), *www.ema.gov.sg/*. Accessed November 2012.

Smartgrid.gov (n.d) "Oncor Electric Delivery Company (Dynamic Line Rating)", *www.smartgrid.gov/project/oncor_electric_delivery_company_dynamic_line_rating*. Accessed November 2012.

Smith, K. and M. Quibell (2010), "Technology in Commercial Buildings: A Key to Scaling Up Demand Response", Johnson Controls, August 2010.

Stennet, D. (2010), "Smart Grid Initiatives—Jamaica's Experience", presentation at the IN-ECLAC Smart Grid Conference, Santiago Chile, October 12–13, 2010, *www.cepal.org/drni/noticias/noticias/8/41128/DStennet.pdf*. Accessed November 2012.

Strother, N. and B. Gohn (2012), "Smart Grid Deployment Tracker 4Q11", Pike Research, *www.pikeresearch.com/research/smart-grid-deployment-tracker-4q11*. Accessed November 2012.

Takada, K. (2011), "Smart Grid Development in Japan", NEDO (New Energy and Industrial Technology Development Organization), August 25, *http://esci-ksp.org*.

Wakefield, M. (2011), "EPRI Smart Grid Demonstration Initiative and Early Results", presentation at the 2011 GreenGov Symposium, Washington, D.C., October 31–November 2, *www.greengov2011.org*.

Wind Power Prognosis (n.d.), "nordpoolspot", *www.nordpoolspot.com/Market-data1/Power-system-data/Production1/Wind-Power-Prognosis/ALL/Hourly/*, accessed November 2012.

Wonderware (2012), "Wonderware Powers Oregon Electricity Demand", *http://global.wonderware.com/EN/Success Stories/2008 PortlandGeneralElectric.pdf.* Accessed November 2012.Wright, K (2011), "2011 Utility of the Year: OG&E", Electric Light and Power, December 2011, *www.elp.com/articles/print/volume-89/issue-6/features/2011-utility-of-the-year-oge.html* Accessed November 2012..

Zuercher-Martinson, M. (2011), "Smart PV Inverter Benefits for Utilities", *Photovoltaics World*, November 2011.

IRENA
International Renewable Energy Agency

IRENA
C67 Office Building, Khalidiyah (32nd) Street
P.O. Box 236, Abu Dhabi,
United Arab Emirates
www.irena.org