Grid Integration of Renewable Energy: Flexibility, Innovation, Experience

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Abstract
The electric power sector around the world is undergoing long-term technical, economic, and market transformations. Part of these transformations is the challenge of integrating high shares of renewable energy, particularly variable wind and solar. The concept of flexibility of a power system is key in terms of balancing these variable sources while keeping the lights on. On the supply side, flexibility arises from innovations in flexible coal and gas power plants, energy storage, and renewables. On the demand side, many distributed resources—generation, flexible demand, storage, and electric vehicles—can also contribute; and likewise transmission and distribution networks, grid operations, and market designs. Experience with measures and innovations for grid integration in all these categories is given, from several jurisdictions like Germany, Denmark, and California, where renewables already provide 20-40% shares of electricity and plans to reach 50% exist. Questions point to areas of technology, economics, planning, operations, business, and policy that need further understanding and learning from experience.

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1. INTRODUCTION

The electric power sector around the world is being transformed in fundamental ways, not just technically, but also in terms of policy, markets, finance, and institutions. Electric power companies face some of the greatest challenges in planning, operations, and investment they have ever faced, as well as a paradigm shift in many of the fundamental tenets that have guided electric power systems for the past several decades (1-6). And along with new technologies, a range of new market and business models are emerging, open to a broader array of energy service companies, energy traders, and other market participants (7-12).

Renewable energy is an integral part of this transformation. Over the past twenty years, a diverse range of renewable energy support policies have been adopted in 145 countries globally, technology costs have declined dramatically, and annual investment in renewable energy reached $270 billion in 2015 (13-14). The "global energy transition" is a phrase heard increasingly, not just in countries that have committed to it explicitly, such as Germany, which targets 80% of its electricity from renewable energy by 2050, or Denmark, which targets 100% by 2035. Many sub-national jurisdictions have ambitious targets for renewables as well, such as California (50% by 2030), Scotland (100% by 2020), and South Australia (33% by 2020). More than 160 countries globally have future targets for renewable energy (13). In addition to these policy targets, many future energy scenarios show high shares of renewable energy globally and for specific regions, with many projections showing 40-80% share of electricity by 2050 (15-22).

A central challenge of the power sector now and in the future is how to integrate higher shares of renewable energy. This is often referred to as the "grid integration challenge." Although there is no commonly cited definition of "grid integration," the California Public Utilities Commission (CPUC) offers this definition: "the process to achieve grid integration is to solve a set of three interlinked challenges, and to harness the opportunities created by these challenges: (a) to integrate wind and solar resources, in increasing amounts, onto the grid, particularly at the bulk or transmission level; (b) to respond to the changes in system-wide customer load due to increased rooftop solar installations and connected electric vehicles; and (c) to bring about, in concert: changes to the characteristics of traditional resources, changes to the functionality and role of distributed energy resources, changes to operational and planning practices at both transmission and distribution levels, and changes to wholesale and retail markets and tariffs" (23).

The grid integration challenge encompasses many elements. Key among them is the concept of "flexibility" of a power system, in terms of balancing "variable" wind and solar resources in particular, and more generally in terms of how all elements of a power system, on both supply and demand sides, can work together to ensure reliability ("keep the lights on") while minimizing cost (24). Another key element is the design of electricity markets themselves, in ways that aid grid integration, while ensuring the most economically efficient operation. A further element is the planning and strengthening of transmission grids to balance geographical patterns of renewable energy resources and power demand. One final element is how distribution-level systems can be transformed in their planning and operation, to support grid integration and flexibility. All of these elements are reviewed in this paper.

There is a large and fast-growing literature on many aspects of renewable energy integration into the power sector. A vast amount has been published in just the past few years, at an accelerating rate. A lot of the literature is technical or engineering in nature, but a growing share concerns the planning, markets, institutions, regulation, economics and business models that accompany the transition to higher shares of renewables (2-12, 23-45). This article looks at a key aspect of this literature—the flexibility or balancing challenge of ensuring that "the lights stay on" in the face of high shares of variable renewable energy sources, particularly wind and solar. In 2015, wind and solar power made up over 90% of total global investment in all forms of renewable energy, and in the future these two "variable" sources will almost certainly continue to dominate power grid transformations (13).

Research and literature on the grid integration challenge is disparate and complex, and often grounded in a specific geographical scope delineated by the technical reach of the power grid itself, and/or by the jurisdictional boundaries of electricity markets, institutions, and regulation. Each of the elements of the grid integration challenge mentioned above is the subject of its own literature, and also can be found in works addressing the broader scope of the whole challenge for a particular power system or jurisdiction. Research and literature on how grid integration can be implemented in the most economic way possible depends very much on the configuration and characteristics of an individual power system and electricity market. No two jurisdictions have the same characteristics, so research is typically very jurisdiction-specific.

2. GRID INTEGRATION GLOBALLY—PRESENT AND FUTURE

In discussing grid integration, it must be recognized that the "prevailing wisdom" of twenty years ago among most electric power companies and power engineers was that going above 5-15% shares of "variable" or "intermittent" renewables like wind and solar would spell doom for the reliability of the power grid, and "the lights would go out." Going above that limit would only be possible with large amounts of expensive energy storage. Such prevailing wisdom of the past is clearly wrong, given the high levels of renewable energy penetration already seen today in many jurisdictions, while the lights remain on and little energy storage has yet to be employed beyond pumped hydro. Several jurisdictions are already near or above 20% shares of variable renewables. And targets for higher shares in many jurisdictions are being accompanied by planning for grid integration that involves only modest amounts of energy storage, coupled with many other grid integration measures considered to be cheaper and more practical.

California is a good example. In 2015, California received over 20% of its electricity from renewable energy (not counting large hydro). By 2020, California's Renewable Portfolio Standard policy requires a 33% share of renewables (also not counting large hydro). By 2020, a big part of California's renewables will be solar power, which has been growing rapidly due to continuing state and federal incentives. California's power companies, regulatory authorities, and power grid operator are addressing the grid integration challenge successfully, and anticipate little difficulty through 2020. According to an analysis by the California Public Utilities Commission, the characteristics of California's existing grid infrastructure have allowed for successful integration of variable wind and solar generation with only minor changes to grid operations (24). Beyond 2020, new state legislation enacted in 2015 targets 50% renewables for California by 2030, putting the state on a clear path to addressing grid integration in new ways through 2030 (46). Several recent studies have looked at California's grid integration challenge (23, 47-53).

Along with California, Germany is also a global leader in adopting high shares of renewable energy. Renewables already provide close to 30% of Germany's power on an average basis (54). On some peak days in 2014, solar and wind alone supplied close to 80% of peak power demand at specific times of the day. Germany is targeting a 50% share of renewables by 2030 and 80% by 2050. Germany has not faced major difficulties with grid integration yet, so far successfully balancing its variable renewables with power imports and export to neighboring countries, a well-functioning electricity market that allows negative-price curtailment, strong grids, an oversupply of generation capacity, and higher degrees of operational flexibility of its coal and nuclear plants (32, 40, 53-55). Germany is beginning to comprehensively confront the grid integration issues that will arise in the future. For example, the German government recently issued a "white paper" that proposed changes to Germany's basic electricity law and market, including measures that could assist with grid integration (56). The organization Agora Energiewende publishes a comprehensive literature on Germany's future grid integration challenges (57).

Denmark is a world leader in wind power, with 39% of the country's electricity coming from wind in 2015 (58). Denmark is targeting 50% of its electricity from wind power by 2020, and 100% of its electricity from all forms of renewables by 2035. These ambitions have put Denmark at the forefront of grid integration, with many strategies implemented or planned (32, 40, 43, 53, 58-60). So far, cross-border market-based power exchanges with neighboring countries, flexible coal plants, flexible combined-heat-and-power plants coupled with thermal storage, "must-run" capacity, ancillary service innovations, day-ahead wind output forecasting, and advanced power-grid operational measures have all allowed Denmark to successfully integrate and balance its renewables. Indeed, there have already been individual days when wind power has supplied more than 100% of the country's power demand. In the future, Denmark will be further integrating its heating, transport, and electricity sectors into a transformed energy system that balances very high shares of variable renewables.

Many other jurisdictions around the world are addressing the grid integration challenge as the share of renewable energy grows. In the U.S., beyond California, the MISO (mid-west), PJM (mid-Atlantic), New York, ERCOT (Texas), and Hawaii power grids are all undertaking or considering a wide variety of measures for transmission, demand response, distributed generation, market design, ancillary services, and/or distribution systems, in parallel with national policy changes by the federal energy regulator FERC (2, 32, 61-65). In Europe, a number of EU-wide initiatives are underway related to grid integration by 2020 and beyond, including transitions in EU electricity market designs, long-term transmission planning, and planning flexible coal and gas plants (41, 66-68). The EU as a whole had a 27% renewables share in 2014. Among individual EU countries, Italy is targeting distributed energy storage in areas with high shares of solar power. Spain, a wind power leader, pioneered advanced grid controls and wind forecasting and has relied on its hydro resources for balancing, in addition to planning for larger grid balancing areas. Ireland, also a leader in wind power (supplying more than 50% of the country's power on some days), has been undertaking transmission strengthening and a cross-border energy market with the UK, along with better wind forecasting and grid planning (2, 32). Down under, the state of South Australia, with a 30% wind power share in 2014, has also developed advanced wind forecasting and has been grappling with grid flexibility and electricity market volatility given its relative isolation from other grids (40).

Among developing countries, China, India, South Africa, and several others are beginning to respond to the grid integration challenge with a variety of measures as renewable energy development accelerates (2, 40, 53, 69). South Africa is facing the particular challenge of integrating a growing share of distributed solar power within its distribution networks, as well as making coal plants more flexible. In China, a large part of the challenge has been strengthening and extending transmission networks to transfer wind power from remote regions that lack sufficient power demand to absorb the wind power locally, as well as making coal plants more flexible. Measures in India have included transmission planning, strengthening transmission corridors for wind power, renewable output forecasting, and regulatory measures for power market operation and scheduling.

Several countries around the world already have very high shares of renewables, in the 60-90% range, including Austria, Brazil, Costa Rica, Georgia, Iceland, Mozambique, New Zealand, Norway, Sweden, and Uganda (13). But in these cases the renewables are not variable wind and solar, but rather dispatchable hydro, geothermal, and biomass. So the grid integration challenge is less pronounced in such countries.

3. FLEXIBILITY OF POWER SYSTEMS

"Flexibility" is a key attribute of power systems. Power system flexibility has existed since the dawn of electric power networks over a century ago. However, conventional flexibility was based primarily on being able to vary generation output to match changes in load, and also to respond to sudden unexpected changes in power system components such as a transmission line or generator experiencing a fault or accident. So flexibility needs were driven by the accuracy of load forecasting and the probabilities of various discrete events. However, flexibility needs and the meaning of power system flexibility are being re-considered and re-defined—in terms of being able to balance large shares of variable solar and wind resources whose output is not constant or perfectly predictable, as well as accommodate a variety of new technologies like energy storage, electric vehicles, and demand response, all of which are changing the nature of power systems. Over the past decade, there has been a burgeoning literature on the needs, costs, and assessment of flexibility in power systems with increasing shares of variable renewables (24-30, 40-45).

Flexibility Needs and Assessment

The additional needs for flexibility based on variable renewable energy arise in a number of ways. First, the variability of renewable output in real time (seconds to hours) means that the remaining resources on a power system must respond in real time to changes in renewable output to keep the system balanced (see also curtailment in Section 6). This is called the "balancing" timescale. Second, flexibility needs arise from system "ramping" caused by large swings in renewable power output over short periods of time. This may be caused by large and sudden changes in wind output, for example, but most typically by the daily swings in solar output in the morning and evening as the sun rises and sets, leading to large swings in "net load." Third, a longer-term need on the scale of months and years is ensuring that enough resources exist to counter longer periods of low renewable output, requiring "back-up" resources that may only be needed during short periods of the year (see Section 4). For example, during the month of November in particular, Germany sees little wind or sun, so other resources must fill the void.

Flexibility needs for system ramping have become a major concern in California, where the grid operator CAISO predicts a 13-gigawatt (GW) ramp occurring over a 3-hour period each afternoon by 2020, due to solar output declining as the sun sets (23). (This ramp is pictured in CAISO's infamous so-called "duck curve.") Meeting that 13-GW ramp is the equivalent of turning on thirteen nuclear power units over a 3-hour period, every afternoon. In Germany, projected ramps by 2022 reach an unprecedented 40 GW (57). However, Germany proved in 2015 that it is already able to handle a 13-GW ramp today, with little difficulty. This "demonstration" occurred during a mid-day solar eclipse, which caused a 6-GW down-ramp of solar (over 60 minutes) followed by a 13-GW up-ramp (over 75-minutes). Germany's import and exports with neighboring countries, power market design allowing negative prices, and flexible coal plants together handled these ramps with no power outages (55).

Flexibility needs can be mitigated with greater geographical diversity of renewable resources over a strongly interconnected grid, such that the total output of all renewables over the whole grid at any given time is less variable than from any individual source or location, due to geographical diversity (anti-correlation) of wind strength and cloud cover, for example. Flexibility needs can also be mitigated through mixtures of different types of renewable resources that may compliment or balance each other, again leading to lower overall variability. This resource mixture may even include different mixes of solar panel east-west-south orientations, affecting solar output profiles over different times of day. Finally, weather forecasting that can predict renewable output, on scales from minutes to days in advance, reduces the flexibility burden on a power system by allowing renewable output to be precisely modeled and scheduled in advance, thereby reducing the balancing burden to merely the difference between predicted and actual output (see Section 9). Renewables may be variable, but they are highly predictable in advance, as the state of the art in renewable output forecasting has shown, which has profound implications for grid integration that remain underappreciated by many.

A subset of the literature addresses the assessment of flexibility needs. Part of this literature addresses the practical quantification of flexibility using various metrics, some highly technical in the domain of power engineering and some suited to system planners and policy makers (70-73). For example, the EPRI (70) puts forth metrics in a planning context that include Period of Flexibility Deficit, a measure of periods when available flexible resources are less than required flexibility, and Expected Unserved Ramping and Insufficient Ramp Resource Expectation, two metrics related to the probability of being unable to meet ramping needs.

The literature also provides practical frameworks for assessing flexibility needs and solutions. Notable is the IEA Flexibility Assessment (FAST) framework, which first characterizes flexible resources available, then determines flexibility needs, and then compares needs with available resources (26-27). The result is a characterization of how much variable renewables can be accommodated in the "status quo" system, and/or additional levels of flexibility that would be needed. The CPUC (23), in a white paper on grid integration policy through 2030, laid out similar analytical steps (see Sidebar).

Cost of Flexibility/Integration Costs

The additional costs of increasing the flexibility of a power system to accommodate higher shares of renewables are typically called "integration costs" or "cost of flexibility" (26, 74-77). Because each power grid is different, and consequently the measures needed to increase flexibility are different, and because analytical underpinnings are not well developed (including what counts as additional or incremental costs), the field is still relatively undeveloped, and controversy exists over how and what to count.

For Germany, Agora (74) gives integration costs of onshore wind and solar power, counting costs of "grid reinforcement" and "balancing" (ancillary services and forecast errors) as 0.5-1.3 eurocents/kilowatt-hour (kWh), which represent perhaps one-tenth to one-twentieth of the direct costs of renewable power. Agora also adds costs of 0.0-1.0 eurocents/kWh for costs imposed on the conventional generation fleet, in terms of "back-up capacity" and lost revenue, an even more controversial and difficult-to-quantify figure. For Europe as a whole, Pudjianto et al. (77) similarly estimated integration costs of solar power at between 0.5-2.5 eurocents/kWh counting all costs, while also noting that integration costs decline when demand response or energy storage are present. California is among the first jurisdictions to try to apply integration costs to formal regulatory proceedings, and has been developing a "renewable energy integration

Sidebar: Flexibility Analysis Needs in California

The CPUC lays out four analytical needs for attaining, in a least-cost manner, the necessary flexibility for California with a 50% renewables share in 2030 (23).

1. Determine the flexibility implications of existing policies, programs and initiatives, including those for distributed energy resources. How far do the policies and programs currently being implemented take California on the pathway toward sufficient flexibility to achieve its 50% renewables goal?

2. Make improved assessments of flexibility and ancillary services needs based on the existing and planned generation fleet, and the emerging set of distributed energy resources.

3. Conduct a cost-benefit analysis of potential grid integration measures, including supply-side resources, distributed energy resources, and market designs. Show the additional flexibility that could be obtained from existing and new resources, and consider flexibility attributes like ramping speed, ability to modify the net-load shape, and provision of ancillary services.

4. Assess least-cost pathways towards grid integration that account for all potential measures. Compare the costs of curtailment, increased ancillary services, and potential reliability impacts from over-generation under a "status-quo" trajectory to 50% renewables, with the costs of least-cost packages of grid integration measures.

costs adder" to use when calculating least-cost portfolios of renewable energy as part of the state's Renewable Portfolio Standard (78).

The IEA (26) did a groundbreaking study on the economics of power system flexibility that developed two integration cost metrics. The first, called "levelized cost of flexibility" (LCOF), compares the cost of providing flexibility from different measures, including flexible generation, storage, demand flexibility, and distribution network upgrades. LCOF is expressed in units of dollars per megawatt-hour and represents the additional cost for supplying or consuming power more flexibly. The second metric was a benefit-cost ratio of applying a specific flexibility option to a given power system. The study found a wide range of integration costs across all measures considered, and concluded that demand-side measures, distributed heat storage, and district-heating applications might be among the most cost-effective. The IEA study also created new models for combining packages of flexibility measures together and concluded that combinations of measures resulted in cheaper total system costs compared to considering measures individually. This finding was echoed by Agora (74), which also concluded that comparing total system costs of different power-grid scenarios could be more appropriate than measure-by-measure costs.

Flexibility Measures/Innovations

Flexibility can come from both supply-side resources and demand-side resources on a power system. Flexibility also arises from the design and operation of electricity markets, from transmission and distribution networks, and from the technical operation of the grid itself. Long-term power system planning for flexibility incorporates all of these elements. The specific measures and innovations for flexibility are described in the literature both conceptually and based on practical real-world experience. These measures and innovations are reviewed in the following sections.

It should be noted that every power system and electric-power regulatory jurisdiction is different. A blueprint for grid integration in one jurisdiction will most likely have only partial relevance to another jurisdiction. The grid integration challenge can vary greatly in scope and solution based on the properties of individual jurisdictions. The IEA and IEA-RETD (26-29) pioneered approaches to analyzing the conditions that determine flexibility needs and solutions, including the types and geographic spread of variable renewables, the flexibility afforded by dispatchable generation, the strength of transmission and distribution networks, the degree of interconnection with neighboring power systems, the size of the grid "balancing area," the power control/dispatch regimes in use, the dividedness or unity of power markets, and the characteristics of power demand. IRENA (40) characterizes the "ease of grid integration" with three variables: whether grids are isolated or interconnected, whether the power system is growing or already mature/developed, and the speed of renewable energy deployment.

It should also be noted that "smart-grid" technologies enable many of the flexibility measures and innovations discussed throughout this paper. There is already a large literature on smart grids, much of which could be considered part of the "grid integration" literature (11, 79-82). While some of the smart-grid literature focuses more technically on the data and communication tools to enable various measures and innovations, in many works and conventional thinking, "smart grid" is synonymous with "flexible grid." Thus, smart-grid literature also encompasses the broader planning, operational and innovation needs and functions for flexibility and grid integration that are discussed in this paper.

4. SUPPLY-SIDE FLEXIBILITY INNOVATIONS FOR GRID INTEGRATION

Flexible Coal, Natural Gas, and Nuclear Plants

The flexibility of coal and natural gas power plants is based on three basic characteristics: (a) their ability to cycle on and off and the lead time required (i.e., start-up time); (b) their minimum and maximum output range while running; and (c) the ramping speed at which they can vary their output levels. Existing plants will have given levels of flexibility but can be modified (retrofitted) to increase their flexibility, requiring a variety of hardware modifications plus changes to operational practice. New plants being build can be designed for higher levels of flexibility. When employed to balance variable renewables on a grid, flexible coal and natural gas plants may cycle on/off once or multiple times per day, frequently ramp their output up/down, and lower their output to minimum limits (2, 26-27, 34, 83).

In most of the world, coal plants are designed to run at constant output, as "baseload," and rarely to be turned down or off completely. Such plants, usually considered "inflexible," can experience reduced efficiency, increased costs, lower equipment lifetime, and more maintenance if cycled on/off or ramped up/down on a frequent basis. Such consequences led to long-standing "conventional wisdom" that coal plants could not be flexible. However, there are many examples of flexible coal plants in use today, including those that have been retrofitted from their original designs. One example is the Majuba coal plant in South Africa, originally built in 1982, which was re-designed to enable quick start-ups and ramping. Re-designed, the plant can compete in the South African Power Pool, cycling on/off twice daily despite its original baseload design (2). In Denmark and Germany, ramping and cycling of coal plants has long been considered normal practice (53-55, 58-60). Denmark has anticipated the need for flexibility since the 1990s, and coal plants in Denmark have been built to be highly flexible. In Germany, most of the hard-coal plants have been originally designed or later modified for flexible output, while many lignite plants, although less flexible, have been modified in recent years for lower minimum output. Cochran et al. (84) provide a case study of a coal plant in North America that was retrofitted from inflexible baseload to flexible operation with twice-daily shutdowns and low minimum output.

Combined-cycle natural gas power plants are designed to run as baseload or "intermediate" plants. Similar to coal plants, these natural gas plants can be designed or retrofitted to be more flexible, although also with some loss of generation efficiency, higher maintenance costs, and higher emissions (38). A large number of gas turbines now on the market are explicitly designed and marketed as flexible, or "fast-acting" plants, with shorter start-up times and faster ramping rates. One example is the Sloe Centrale combined-cycle natural gas plant in the UK, built in 2009 with flexibility factored into its design, which can ramp to full output in just 30 minutes (2, 85). Simple-cycle gas turbine plants have been employed as "peaking" plants for decades to provide flexibility, although they are less efficient.

Nuclear power plants, generally considered the most inflexible of baseload plants, can also provide flexibility if designed and operated appropriately (27, 86). France and Germany have long designed and operated their nuclear plants for flexibility. In France, nuclear plants provide ancillary services and also act in "load-following" mode, which means they ramp their output up/down in response to changes in load. The Nuclear Energy Agency (86) notes, however, that operating nuclear plants at less than maximum output has been demonstrated to increase unscheduled outages, and that diligent operations and maintenance are needed for safe operation.

The IEA (26) provides a generic characterization of the differences between flexible and inflexible plants. Flexible coal plants offer ramping rates of 4-8%/minute, 2-5 hour start-up times, and minimum output limits of 20-40% (of maximum), compared to inflexible plants with ramping rates of less than 4%/minute, 5-7 hour start-up times and minimum output limits of 40-60%. Flexible natural gas plants show similar improvements, with minimum output limits of 15-30% compared to 40-50% for inflexible plants. A "fast-acting" gas turbine plants on the market today can offer start-up times of just 40 minutes (38). Flexible nuclear plants offer minimum output limits of 30-60%, compared to 100% for inflexible plants. In France, existing nuclear plants can ramp down to 30%, with ramp rates of up to 1%/minute (27).

While power plant owners have emphasized the increased costs, additional wear-and-tear, and reduced equipment lifetimes of coal and gas plants operated more flexibly than originally designed, the IEA (26) concluded that "the cost implications from increased cycling and start-ups may not constitute a very large part of total system costs… particularly as older inflexible plants are retired and more flexible plants added to the system." However, another real financial consequence of more flexible coal and natural gas plants is that plants operated flexibly produce fewer units of electricity per year, and thus less revenue, compared to conventional baseload operation. This consequence, and its impact on the business and economics of power companies and electricity markets, is a fundamental challenge of the "global energy transition." It is one of the reasons why Rogol (12), Sioshansi (7), Gray et al. (87) and many others foresee major shifts in the power industry. This issue also relates to "back-up capacity," "resource adequacy," and "capacity markets" discussed in Section 10.

The most serious effects may first be seen in countries like Germany, where Agora (57) notes that up to one-quarter of all dispatchable power capacity (i.e., coal, gas, and hydro) may operate at full output for less than 200 hours per year by 2020, (otherwise operating at reduced output), along with an across-the-board reduction in annual "full-load hours" for most other plants. This projection is echoed by the IEA (26) in its modeling results, where it notes that in a hypothetical transformed power system, "the power plant mix shows a structural shift, comprising a strong decrease in the number of baseload or inflexible power plants, and an increase in the number of flexible power plants designed for part-time operation." Indeed, the global energy transition and shifts to more flexible plants suggests a fundamental re-conception in the meaning of "baseload," such that renewable plants, by virtue of their almost-zero marginal operating cost, may become the "new baseload" (2, 19, 22, 24, 88).

Flexible Combined-Heat-and-Power Plants with Heat Storage

Denmark, Germany, and several other countries are already using, or considering using, combined-heat-and-power plants (CHP) coupled with heat storage to provide power grid flexibility (2, 26, 54, 58-60). Denmark is the leading example, where over half of all electricity is supplied by CHP, including many small and flexible plants. These plants feed into district heat-supply networks for heating buildings. Most of these networks include large water tanks for heat storage. This whole system was designed starting in the 1980s with flexibility in mind. In many typical CHP plants around the world, operation is driven by heat demand, with electricity as a secondary byproduct, and thus electricity production is not flexible. In Denmark, CHP plants can vary the proportion of heat and electricity, using stored heat to offset any shortfalls if heat production falls below heat demand (i.e., if more electricity and less heat is being produced). This means that CHP plants can vary their electricity output in response to grid conditions and provide balancing.

Economically, this flexibility from CHP was supported by the legal integration of CHP plants into Denmark's electricity market, including capacity payments (subsidies) to keep CHP plants active in the electricity market, so electricity market design has played a key role. Also, many of Denmark's CHP plants are fueled by biomass, which thus provides a long-term pathway for balancing variable renewables with a non-variable but still-renewable resource like biomass. The scheme is a key part of Denmark's long-term integration of electricity, heating, and transport into a single transformed energy system, as well as Denmark's vision to become completely fossil-fuel free. Denmark's experience is relevant to grid integration in many countries, as worldwide, many schemes for district heating and cooling coupled with electricity supply and renewable energy already exist and are growing (89-90).

Electricity and Heat Storage

In the past, the only electricity storage resources generally considered practical for grid balancing were reservoir hydro and pumped hydro. Pumped hydro was often developed in combination with inflexible baseload plants such as coal and nuclear, storing electricity during the night and releasing it during the day. In current and future power systems, the long-standing tenet that instantaneous supply must always equal (and follow) instantaneous demand, is being replaced by the flexibility granted by storage technologies, as well as many demand-flexibility innovations. Many emerging forms of storage allow power systems to become more flexible and accommodate variable demand as well as variable renewable generation, including batteries, supercapacitors, flywheels, fuel cells, and compressed air, along with many forms of heat storage like hot water tanks and phase-change materials. Storage can be incorporated at many locations and levels, such as the bulk-grid level, onsite at wind farms or other power plants, within local distribution networks, or at the building level. And storage can operate on different time scales, from seconds to days. Most grid-integration literature addresses storage, and studies dedicated solely to storage have ballooned over the past decade (91-103).

Many future energy scenarios show growing levels of energy storage on power systems in the coming decades (19-22, 41, 57). However, notable is that storage remains a modest contribution to power systems in the short- and medium-term in many scenarios, by virtue of relatively high cost, and because other grid integration measures can be done first. Many studies show, and many experts suggest, that shares of renewables of up to 40% are possible before storage must become a major contributor to flexibility. For example, Agora (92) studies for Germany show storage only being used after 2032, as Germany approaches a 50% share of renewables. Denmark has no plans for electricity storage, relying instead on heat storage. California has mandated 1.3 GW of storage to be procured by its power companies by 2020, a relatively modest amount as California reaches 33% renewables (23).

A number of energy storage "roadmaps" have been published in recent years, casting light on how energy storage may evolve in the future, considering technologies, policy, economics, and markets (100-102). A California roadmap, jointly created by the grid operator CAISO, the regulator CPUC, and the state Energy Commission, outlines a future series of actions for planning, procurement, rates treatment, interconnection, and market participation. An IRENA energy storage roadmap considers the economics and applications of storage, and outlines priority actions in the areas of system analysis, applications for islands and remote areas, distributed storage, and utility-scale storage.

Storage at transmission and distribution levels is beginning to provide clear economic value to transmission and distribution utility companies. As well, private power developers can sell storage into wholesale and ancillary markets in some jurisdictions where markets allow, or integrate storage with their own generating plants (2, 38). Profitable projects and commercial business models for utility-scale storage are emerging in a number of jurisdictions, including Kaua'i Hawaii, ERCOT (Texas), PJM (mid-Atlantic), and Southern California Edison. One promising storage application has been the integration of heat storage with solar-thermal power plants, which enable these plants to produce power for several hours into the evening after the sun has set, making them appear more like baseload (13, 103).

Firm Renewable Energy Plants

Renewable energy plants such as reservoir hydro, biomass and biogas, geothermal, and concentrating solar-thermal power can also contribute to flexibility. These plants typically can be dispatched similarly to coal and natural gas plants, and can offer flexibility in terms of start-up time, ramping rates, and minimum output limits. The IEA (26) calls such plants "firm" or "dispatchable" renewable energy. Many future energy scenarios, particularly those for very low-carbon/low-fossil-fuel trajectories, show firm renewable resources playing significant roles in balancing variable renewables, mitigating the need for fossil-fuel plants.

Increasingly, jurisdictions with high shares of variable renewable energy are demonstrating that variable renewable energy generators themselves can be controlled and operated in ways similar to dispatchable resources, providing both flexibility and ancillary services (2). (See also following discussions on smart inverters and curtailment.) Denmark, for example, considers wind power part of the solution to grid integration, not just the cause of the balancing challenge. In Spain, grid operator REE was the world's first operator to develop centralized, dedicated monitoring and control of variable renewable energy plants, dating back to 2006. In 2015, REE controlled the dispatch of up to 96% of the Spanish wind power fleet, and was able to change aggregate wind power generation to any given level within 15 minutes. Ireland also appears likely to use its wind power fleet to provide grid flexibility in the future.

5. FLEXIBILITY FROM DISTRIBUTED ENERGY RESOURCES

A wide variety of distributed energy resources can provide flexibility from the demand-side of power systems (2-4, 6, 11, 20, 22, 24, 26, 40, 50, 79, 104). Innovations in flexibility from distributed energy resources include static energy efficiency improvements aligned to grid needs, demand management and flexible demand, time-of-use and dynamic retail rate structures, distributed energy storage options for both electricity and heat, electric vehicle charging and discharging, and distributed generation coupled with "smart inverters." The grid integration literature covers all of these innovations, although more often as separate topics rather than collectively. Overall, the literature on flexibility from distributed energy resources is much less developed and more recent compared to other grid integration topics. Partly this is because real-world experience in employing distributed energy resources for flexibility is still very limited, relative to the long-term potential. Thus, for distributed energy resources, a larger portion of the literature focuses on envisioning what could happen in the future, suggesting new business models and policies, and documenting lessons and experience from demonstration projects.

Responsive Load and Demand Response

Responsive load and demand response innovations provide flexibility by enabling power consumption to vary in response to supply-side variability and grid conditions, and thus allow power demand to play a role in balancing variable renewables (3, 26, 105-113). This means that load can change in magnitude, or time-shift to other periods in response to a variety of conditions. The change in load might occur autonomously in response to time-of-use or dynamic retail prices ("reactive" or "time-based"), to direct control of the load by the grid operator or third-party ("dispatchable" or "incentive-based"), or to the participation of demand response in wholesale, ancillary, or capacity markets. Widespread deployment of smart meters, communications, and other enabling "smart grid" technologies facilitates these innovations.

Demand response is most suited to loads that can be time-shifted to later periods without serious consequence, such as freezers/cold storage, heating, water pumping, and some industrial processes, particularly if enough inertia or storage capacity is present in whatever is being time-shifted. A larger class of interruptible loads can participate as load shedding, rather than shifting, where demand simply goes unserved. To date, most demand response in the United States has been employed as ancillary services, to be used only infrequently under emergency system conditions, perhaps tens or hundreds of hours per year (105, 106). However, examples of demand response employed to provide power system flexibility on a regular (i.e., daily) basis are emerging slowly around the world. In 2014, Germany had about 1 GW of demand response feeding into its ancillary markets. California's power companies were procuring limited amounts of demand response under regulatory mandate (23). Direct bidding of demand response as a flexible resource into wholesale, ancillary, or capacity markets has been emerging in some jurisdictions, for example PJM (mid-Atlantic) in the United States (64). Examples of long-term power system planning that has started to incorporate demand response as a resource in long-term plans can be found in California, the Canadian province of Ontario, France, and South Africa (2).

New “aggregator” business models are also part of the picture. An aggregator company might contract with hundreds or thousands of power consumers, allowing the aggregator to control certain elements of their power consumption upon receipt of a control signal. The aggregator can then sell that aggregated demand flexibility to the grid operator, to be activated at the request of the grid operator, or the aggregator could bid demand reduction into wholesale or ancillary electricity markets, in the same ways as power generation is bid into these markets.

Electric vehicle “smart charging” is a form of responsive load, where charging regimes can respond to dynamic rates or control signals to shift charging demand into the most favorable periods for the grid, subject to driver requirements for travel (113). Beyond smart charging are “vehicle-to-grid” (V2G) and “vehicle-to-home” (V2H) concepts, where electric vehicles become an integral part of the power grid and/or home energy system, and can dynamically charge or discharge in response to external signals or dynamic prices (11, 104, 114). Emerging examples of such models can already be found in Scotland, Japan, and Hawaii (2). An aggregator could also aggregate the behavior of large numbers of electric vehicles and sell their battery capacity into the grid, charging or discharging in response to grid needs for flexibility (depending on market design and pricing).

Time-of-use and dynamic retail rates have traditionally been used to reduce load at peak times of day, when power system resources are most strained. But the application of such rates to creating flexibility at non-peak times is relatively new, for example during swings in wind power output at whatever time of day, or to compensate for afternoon ramps as solar output declines. This can result in novel situations, such as low rates at midday to encourage more demand if solar output is high, and higher rates later to discourage demand as solar output declines. Some jurisdictions are just beginning to consider how time-of-use and dynamic rates can be applied to flexibility needs, or are engaged in dynamic pricing pilots, such as California, Connecticut, Oklahoma, and Washington DC (2, 23).

Distributed Generation and Distributed Energy Storage

Distributed generation, typically small-scale biomass or wind or rooftop solar, can also provide flexibility to the power grid, typically by reducing its output, although in some cases by increasing its output (e.g., if previously held back on purpose to allow later increases). This can occur autonomously under some programmable regime, or when directly controlled by the grid operator, or when aggregated by an aggregator and sold into wholesale or ancillary markets. For distributed solar power, this typically happens through control by a “smart inverter” (79, 115). Technical standards, protocols, and regulatory frameworks for smart inverters are emerging in several jurisdictions, including California, Hawaii, and Germany (2). In Germany, all solar systems larger than 30-kW are required to be controllable by the grid operator. Smart inverters or technically-capable wind turbines can also provide other technical services to local distribution grids, such as voltage and reactive power support.

As discussed earlier, many forms of energy storage can provide flexibility, including distributed storage at the local or building level. In many jurisdictions, there is growing interest in household-level battery storage, primarily in conjunction with rooftop solar power. However, the economics of household-level storage depend greatly on the policy situation facing the household. Under a “net metering” policy common in the U.S., there is no economic incentive for storage because any power can be sold to the grid at the retail price. In jurisdictions where retail prices are higher than the grid buy-back rate for power, such as Germany, then the “self-consumption” economic model for distributed solar power becomes more profitable, where power that is self-generated and self-consumed, for example through a local battery, has more economic value to the consumer than power that is sold to the grid (116). Local battery storage can also reduce peak-demand charges for commercial customers if they face capacity charges. Governments and/or power companies in some jurisdictions are beginning to provide incentives or foster distributed energy storage coupled with solar power, including California, Italy, Japan, and New Zealand (2). For example, the distribution utility Vector serving the city of Auckland, New Zealand is installing batteries with rooftop solar, employing these batteries to reduce peak capacity charges it pays to the transmission grid operator.

Thermal loads and storage have long been utilized to shift daytime electricity loads to nighttime for cost savings and to reduce power system peak loads. This same concept is now being utilized in shorter time intervals and at different times of day to support balancing of variable renewable energy generation, cost reductions, demand response, and decreased system peak loads in conjunction with smart communications and controls. A variety of thermal loads and storage are being employed to provide demand response, including chillers in commercial buildings and electric water and space heaters in homes, sometimes coupled with thermal storage (2).

The concept of a "virtual power plant" is another emerging innovation for balancing renewables that has entered the literature, so far mostly in advancing the concept and documenting the experience from various demonstration projects that incorporate virtual power plants (45, 56, 117-119). A virtual power plant is some combination of distributed energy resources bundled together, such as distributed generation, storage, demand response, and electric vehicles, which all may be individually small and disparately located. Connected together via smart grid links, with control and accounting systems, this virtual block of resources can become a dispatchable resource to the grid, can provide ancillary services, or can be used in local power networks and markets.

6. CURTAILMENT OF RENEWABLE GENERATORS

As more renewable energy is added to power grids, curtailment has emerged as a common response to grid integration (61, 120-125). Curtailment may occur: (a) if there is too much generation at a given time (an "overgeneration" condition) and other generators can't reduce their output fast enough or have reached their minimum output limits; (b) if there is not enough transmission or distribution line capacity to handle the renewable output; or (c) because of other grid conditions. Curtailment of wind and solar power plants causes a downward adjustment in their output, in spite of their potential to generate more power given prevailing wind or solar conditions. Thus, curtailment results in "spilled" or "wasted" generation that could have come from the renewable generator but is instead lost. Curtailment is often viewed negatively, and the "repercussions of discarded energy" can include lost revenues, lost incentives, and increased business risk.

There are different types of curtailment, sometimes causing confusion. The CPUC (23) defines "manual curtailment" as that ordered by the grid operator in response to system-reliability conditions and accomplished through exceptional dispatch (direct instruction to reduce/cease output); this is also called "involuntary curtailment" and generally regarded as undesirable. "Economic curtailment," on the other hand, occurs through the wholesale market, when renewable generators voluntarily reduce their output in response to market conditions or protocols, for example a negative wholesale price (see Section 10). Definitions of curtailment vary by jurisdiction (61).

A number of jurisdictions with high renewables shares around the world currently face curtailment issues (61, 120). China is experiencing the highest levels of wind curtailment of any jurisdiction, with some provinces curtailing 15-25% of wind power output due to insufficient local demand coupled with lack of transmission capacity to other provinces (2, 121). Other countries with high levels of wind power, including Spain, Italy, and Ireland, have seen much lower levels, typically in the 1-3% range. Denmark and Portugal have virtually no forced curtailment. Among U.S. states, curtailment levels have declined in recent years, and in 2013, wind power curtailment levels were typically less than 2%. Typical reasons given by U.S. states for curtailment are transmission constraints, high wind ramps, and voltage control. In jurisdictions with high amounts of solar, such as California, Germany, Italy, and South Australia, very little solar curtailment yet occurs, although Hawaii and Japan face unique situations.

There is a large literature on the economics of curtailment, including the economic losses associated with curtailment, as well as methods to determine the "economically optimum" levels of curtailment that balance the added costs of grid flexibility or network upgrades necessary to reduce curtailment, against the economic losses of curtailment (122-125). One of the key variables is the degree to which business contracts with renewable generators, market rules, and/or regulatory provisions assign the economic losses of curtailment to the generator, rather than to the grid operator or to other market participants. Each jurisdiction is different.

7. TRANSMISSION STRENGTHENING AND GRID BALANCING AREAS

Transmission grid strengthening can be an important measure for grid integration of renewables, in terms of: (a) balancing a broader geographical diversity of resources to reduce flexibility needs, (b) facilitating cross-border exchanges of renewable power, (c) integrating markets together to create more flexibility, and (d) providing access to geographic regions of high-concentration or remotely-located renewable resources. "Transmission planning" has always been a core component of power system planning, but over the past two decades, transmission planning that specifically addresses these goals has emerged as a discrete topic of research and policy (2-3, 22, 24, 26, 28, 31, 34, 40-41, 57, 65, 67-68, 126-129).

Many examples exist of transmission planning and investment for serving high-concentration or remote geographic regions of renewables development (2). China, where much wind development has occurred in remote areas, is planning transmission for a series of mega-scale concentrated wind power "bases" in at least eight provinces. Denmark's grid operator proactively plans new transmission capacity anticipating future interconnection of wind farms. Germany has been planning three major north-south DC transmission lines to relieve the imbalance in locations of wind generation versus the locations of power demand. Many regions of the U.S have extended transmission to remoter wind power areas, and new regulatory frameworks at state and federal levels have required or supported such planning, such as Texas's "competitive renewable energy zones" regulatory process. Mexico developed a new planning process called "open season," which identifies transmission needs based on planned wind capacity and guarantees authorization of new transmission.

Transmission capacity for regional interchanges of power can also support grid integration, and many large-scale schemes have been proposed, such as an EU "supergrid," a North Asia "supergrid," the EU-North Africa "Desertec" concept, and the "North Sea Countries Offshore Grid Initiative." Already in Europe, flows of hydropower from Norway and Sweden to neighboring countries provide significant balancing capacity for those neighbors.

A variety of studies have shown that strengthening interregional transmission capacity and planning, and expanding grid "balancing areas" to cover larger geographic territories can increase the flexibility of power systems for integrating renewables. Classic in this field were the NREL Eastern States and Western States integration studies (127-128). Higher shares of wind and solar increase the value of expanded balancing areas, which can provide more load diversity and generation reserves, as well as greater "geographic smoothing" of the variability of wind and solar resources (e.g., anti-correlations across interconnected territories/locations).

Many real-world examples of coordinated transmission planning and balancing area coordination exist. The European Network of Transmission System Operators for Electricity (ENTSO-E) annually develops a ten-year network development plan and regional investment plan among its members. In the United States, the Federal Energy Regulatory Commission requires regional transmission planners to analyze alternative options and develop regional plans. Other examples of interregional coordination and planning can be found in the West Africa Power Pool, the ASEAN Power Grid initiative, and the South Asia region (2, 130).

8. DISTRIBUTION SYSTEMS

The distribution system is the part of the grid closest to end-consumers. Historically, distribution utility companies have not had to be innovators, as their job of load forecasting, grid expansion, and component replacement was relatively straightforward. And as regulated monopolies or state-owned entities in most jurisdictions, distribution companies receive a simple fixed return on capital invested or fixed budgets. With the advent of a wide array of distributed energy resources, the job of planning and operating distribution grids is getting more complicated, and the traditional business models and regulatory frameworks of distribution utilities are primed for future transformations.

In the future, distribution utilities will need to plan, operate, and innovate in a variety of new ways—to manage distributed generation, two-way power flows, demand response, storage, smart inverters, electric vehicle charging, micro-grids, and a host of other trends. Distribution utilities will need to monitor, collect, analyze, and use data about their grids in completely new ways, and will need to analytically model their distribution systems to a degree far beyond current practice. Along with "smart grid," some call this the "smart utility" of the future. A growing and diverse literature addresses these trends and the grid integration of renewables at the distribution level (3, 11, 22, 42, 79-82, 119, 131-135).

Among the many potential transformations, new forms of energy-service businesses are emerging alongside traditional utility business, including the "aggregator" and "virtual power plant" models discussed in Section 5, micro-grids, and peer-to-peer energy exchange. And new local energy markets may emerge, operating semi-autonomously to buy/sell and balance local renewable resources with local storage and demand response. Two examples of visions for such local energy markets and self-balancing are New York's "Reforming the Energy Vision" initiative, which also envisions local distribution grids providing ancillary services to the grid, and the distribution utility EWE in northwestern Germany (119, 132). Many distribution utilities are piloting smart-grid demonstration projects, as well as fundamentally re-examining how to handle distributed generation, particularly utilities facing rapidly growing shares of rooftop solar, such as Hawaiian Electric with its "Distributed Generation Interconnection Plan" (2). And regulators are grappling with a host of issues, such as tariffs, smart-inverter standards, control and data protocols, rules governing physical interconnection to the grid, and regulatory classification of resources.

9. POWER SYSTEM OPERATIONAL MEASURES

There are many power system operational measures that have and can be taken to assist with grid integration of variable renewables. These measures have often been among the earliest steps taken in jurisdictions facing increasing shares of variable renewables, and among the most cost-effective of all measures because of the relatively small amounts of investment required. Many operational measures are rooted in innovative analytical methods and modeling of power systems, while others relate to market design and protocols. Operational measures are typically taken by the grid operator. One early step grid operators have taken when faced with higher shares of renewables is upgrading their power control and dispatch software, communications, and monitoring. Indeed, as wind power grew in Spain in the 2000s, the grid operator REE built a new control center dedicated to wind power.

This section outlines a selection of operational measures. Jones (25) has published a unique and comprehensive compendium of grid integration literature, a large share of it devoted to operational measures. Other good references for non-engineers include MIT (3), IEA (26), and UCS (136).

Gate closure. In a power market, where resources are scheduled in advance (typically day-ahead through real-time scheduling), gate closure is the point before actual generation occurs, by which time a resource is committed and can't be changed. A shorter gate closure time allows variable renewables to be scheduled more accurately, reducing imbalances and the need for flexibility. For example, Texas implemented a 5-minute gate closure, compared to the European EEX market with 45-minute gate closure (26).

Dispatch interval length and transmission intervals. Dispatch interval is the time between each new market auction and schedule for generation. In many jurisdictions dispatch intervals are hourly, but shorter dispatch intervals allow dispatch to adjust to renewable variations more quickly and accurately, reducing the balancing needs from system reserves. Some jurisdictions like California, Germany and Denmark have reduced dispatch interval length to 15 minutes or 5 minutes. Similarly, transmission line scheduling intervals can also be reduced; for example U.S. FERC Order 764 shortened intervals from 1 hour to 15 minutes (62).

System reliability calculations. Methodologies and processes for system reliability calculations (called "n-1" contingency events) have evolved in many jurisdictions to incorporate the effect of renewables. In Europe, the coordinating organization of EU grid operators, ENTSO-E, began EU-wide reliability coordination in the face of increasing shares of variable renewables.

System reserves. Grids must maintain minimum levels of reserves for system balancing and responding to contingencies. Variable renewables create a greater need for reserves (137-138). The IEA (26) suggests that alternative methods of determining necessary reserves, breaking with deeply-rooted practice and tradition, could reduce reserve needs of renewables. Examples include new analytical methods to look at the probabilities of simultaneous events occurring (using renewable forecasts), or dynamic reserve allocation that changes reserves as the level of renewables' variability changes (i.e., partly cloudy vs. sunny days). The IEA notes that "institutional 'inertia' may pose a significant barrier to revising the definition and size of reserves."

Ancillary services from variable renewables. If variable renewables themselves can provide reserves, i.e., if they can contribute to ancillary services, then reserve requirements from other dispatchable generators can be reduced. A number of recent studies discuss the potential for wind and solar resources themselves to provide ancillary services. Such provision already exists in Denmark and is an emerging feature in some other jurisdictions (2, 48, 52, 59-60, 138-140).

Grid codes. Grid codes are the technical, operational, and planning requirements and rules for power systems, such generator interconnection and operation, grid operation, generation and transmission planning, and market rules for balancing, congestion management, and capacity allocation. A variety of literature proposes enhanced grid codes for integrating renewables (141-142).

Wind and solar forecasting. The incorporation of advanced wind and solar output forecasting, based on weather forecasting on timescales from day-ahead to real-time, has become common and highly sophisticated in jurisdictions with high shares of renewables (143-145). Such forecasting has made a major contribution to integrating and balancing high shares of renewables, more than most realize. Denmark has taken this innovation farther than most. In real time, the Danish grid operator updates wind forecasts and compares actual wind output against predictions made the day before. This information is then used to better forecast wind output over the coming hours. This process "virtually eliminates errors" in the predictability of wind output, said one senior manager of the grid operator (53).

10. ELECTRICITY MARKET DESIGN FOR GRID INTEGRATION

Electricity market design is a highly complex subject that really dates back to the 1980s, when restructuring ("liberalization") of the power sector got underway in many countries, and electricity systems began to shift from being vertically integrated regulated or state-owned monopolies to being unbundled market-based sectors with competition at various levels. Market designs vary greatly around the world, and keep evolving with successive rounds of restructuring, de-regulation, or re-regulation. Sioshansi (1) provides an excellent volume exploring current market issues and market evolution in many jurisdictions around the world.

Many aspects of market design have an important bearing on grid integration of renewable energy, and a growing literature focuses on how market designs can evolve to better support grid integration and deliver flexibility in a least-cost manner (2, 26, 32, 40-41, 56-60, 146-148). This subject would require an entire paper by itself, but a few issues are highlighted here.

Negative prices. Negative and zero electricity market prices have become an effective market mechanism for balancing variable renewables, by reducing generation during "overgeneration" conditions, rather than requiring the grid operator to force curtailment of renewables directly (148). In Germany, negative prices cause coal and gas plants to reduce output, and/or export their power to neighboring countries. "Negative prices are not necessarily a bad thing," notes Agora (57), but they do add economic costs to Germany's feed-in-tariff system. Negative prices may also serve as an indicator of relative lack of flexibility of dispatchable generators, so declines in the incidence of negative prices may indicate growing grid flexibility.

Capacity markets and resource adequacy. In the long-term, electricity system operators, planners, and regulators must ensure that enough power capacity exists as power plants are retired and new plants built, a regulatory and planning process often called "resource adequacy." There are ongoing debates in literature, and in individual jurisdictions, as to the best ways to ensure resource adequacy. Options include direct regulatory requirements, capacity mandates, capacity payments, capacity markets, and "must run" obligations. Some jurisdictions rely on energy-only markets without regard to capacity. As shares of variable renewables increase, the challenge increases to ensure resource adequacy, and uncertainty exists as to which options will or won't work in the long term. In recent years California introduced separate "flexible capacity" requirements into its resource adequacy process (23).

Markets for regional power exchange. Integrated cross-border power markets can increase system flexibility and balancing, as amply demonstrated by Denmark's strong interconnection and integration with European and Nordic electricity markets that provides a strong component of Denmark's balancing needs. Germany also benefits from the European Energy Exchange (EEX) for balancing. California and several western states are currently developing the concept of an "Energy Imbalance Market" that would allow neighboring power grids to help balance each other, and potentially reduce curtailment and ramping issues, with different levels of market integration possible (23).

Ramping markets. System ramping capacity has become a potentially key element in market designs for integrating renewables, particularly solar, which can create large morning and afternoon ramps. One example of a ramping market is California, which was in the process of introducing a new market called "Flexible Ramping Product" (23). In this fast-response 5-minute-interval market during ramping periods, the grid operator pays generators to remain off, so that they are available to turn on during a subsequent 5-minute interval if ramping needs exceed forecasts. The payments for remaining off compensate the generator at the market price while off. Generators can voluntarily bid flexible capacity into this market and potentially earn extra revenue compared with the normal market. The market will be open to solar, wind, and storage resources as well.

11. CONCLUSION: RESEARCH, POLICY, AND LONG-TERM PLANNING

Research on grid integration suggested by this review covers a number of topics, including:

(a) Flexibility assessments for specific jurisdictions, including existing levels of flexibility, flexibility needs, flexibility measures, and least-cost combinations of measures that meet future needs. What flexibility benchmarks exist? What flexibility characteristics of dispatchable generation and energy storage are possible, at what cost? What is the special role of combined heat-and-power plants coupled with heat storage? Can variable renewables themselves contribute to flexibility?

(b) Roles and flexibility possible from distributed energy resources such as distributed generation, energy storage, electric vehicles, demand response, and energy efficiency. What are the potentials considering time-of-use and dynamic rates, end-use equipment, aggregator business models, electric vehicle charging regimes, and opportunities for embedded electrical and thermal energy storage? How might these resources provide grid services? What tariffs, standards, control protocols, regulatory classifications, business models, and policies are necessary to unlock the potential of these resources?

(c) Transmission network planning including grid integration considerations. What are the needs and opportunities for transmission strengthening, interconnection, and balancing area expansion? What policies can foster transmission to regions of high renewable resources? What types of transmission are feasible given social and environmental constraints? What are alternatives like distributed resources, market design changes, and flexible generation that might be cheaper than transmission strengthening?

(d) New models of distribution system planning and operation. How should distribution grids evolve to serve two-way power flows, data monitoring and analysis needs, storage, and demand response? What will be the relative roles and relationships of distribution utility companies, aggregator companies, energy-service companies, consumers, and the grid operator? Who will control distributed energy resources in which markets? How might market boundaries change between bulk-grid-level and distribution-level?

(e) Long-term power system planning that considers the full range of flexibility measures and innovations. Considering all the possibilities for additional flexibility to integrate variable renewables, what are the least-cost approaches and least-cost combinations of measures? What are analytical frameworks and tools for determining least cost? Should incremental "integration costs" be used, or should total system cost under different scenarios drive planning?

(f) Reliability, ancillary services and curtailment. How much curtailment occurs, of which types? What are the economic losses associated with curtailment, and who bears them? Under what circumstances does over-generation create real reliability issues? What is the "economically optimum" level of curtailment, given resource mixes and contractual arrangements? How do the needs for ancillary services change, and what are new ways to meet those needs, including from renewable generators?

(g) Electricity market designs and protocols that respond to the needs of grid integration. How will market designs affect the quantity of flexible resources in the future? What are the potential roles of capacity markets; ramping markets; inclusion of distributed generation, storage, and demand-response into wholesale and ancillary markets; local energy markets at the distribution-system level that may be semi-autonomous or self-balancing; peer-to-peer energy; negative market prices; economic curtailment of renewables; and resource aggregators? How can cross-border integration of markets facilitate greater interregional interconnection and balancing?

(h) Policy and regulatory frameworks that support grid integration. Policy makers face future challenges of understanding and analyzing grid integration; working across different technology, investment, and procurement areas that may currently be regulated separately; capturing the potential of integrated distributed energy resources; and working with grid operators to achieve least-cost outcomes. How should policy and regulation proceed, while maintaining reliability, safety, and environmental goals? What institutional changes are suggested, considering electricity, heating, and transport together, and considering the interests of electricity market participants?

The answers to these questions are not simple, and such inquiries will continue well into the coming decades. The answers, and the policy, business, planning, and operational transformations implied by the answers, will lead to a high-renewable-energy future at the least cost, with all the consequent environmental, economic, security, and social benefits.

SUMMARY POINTS

1. Grid integration is of growing importance for attaining high shares of renewable electricity in power systems of the future. A number of jurisdictions with already-high shares of renewables are amassing a wealth of real-world experience with grid integration today, such as China, Denmark, Germany, Ireland, South Africa, and Spain, and states like California, Hawaii, Texas, and South Australia.

2. Shares of renewable energy in many power grids and jurisdictions around the world are already reaching 20-40% today, including large portions of variable renewables like wind and solar, and grids are managing to balance these shares with a wide variety of measures and innovations, with only modest amounts of energy storage.

3. Flexibility is a key attribute of power systems for the integration of large shares of variable renewables. Flexibility already exists, but more is needed, and can come from many different measures and innovations, including supply-side resources, demand-side resources, improvements to transmission and distribution grids, operational measures, and market changes.

4. Assessments of existing flexibility levels, future flexibility needs, costs of flexibility, and least-cost combinations of measures are needed, but assessment tools are relative undeveloped. And because all power systems and markets across the world are uniquely different, solutions are extremely jurisdiction-specific, although measures themselves can be understood generically.

5. Distributed energy resources such as distributed generation, energy storage, and demand response have a potentially strong but relatively less understood role in future power system flexibility. Many new innovations and "smart-grid" technologies, along with new energy-service business models like aggregators and new regulatory frameworks, can unlock these potentials.

6. Market designs and protocols can and should evolve in response to flexibility needs of variable renewables in a variety of ways, including pricing, dispatch/schedule intervals, ancillary service (balancing) markets and requirements, capacity markets or other forms of resource adequacy, regionalization of power markets, and ramping.

7. Power system operational measures, including advanced renewable energy forecasting (weather forecasting), are among the cheapest and earliest measures. Curtailment of renewables and/or negative market prices are among the ways renewable variability can be balanced, and although both are generally considered economically undesirable, they both have a role to play.

8. Policy makers and regulators face the challenge of understanding and analyzing grid integration, working across different technology areas (and regulatory divisions), capturing the potential of distributed energy resources, and working with grid operators to achieve least-cost outcomes. Long-term planning and regulation should consider the full range of flexibility measures and innovations.

DEFINITIONS OF SELECTED TERMS

Ancillary/grid/system services. Generators respond to grid operator signals to keep the grid operating within required parameters of power balance, voltage, reactive power, and frequency

Balancing area. The geographic and technical scope of a power grid in which supply and demand must be continuously balanced, typically controlled by one "balancing authority"

Baseload. Power plants that generally run continuously at constant output year-round, or power plants with the lowest marginal operating costs that are always dispatched first

CHP. A power plant that produces both heat and power simultaneously, providing heat as hot water or steam to nearby buildings or industries

Dispatchable resources. Resources that the grid operator can directly control, dispatched according to market scheduling or as ancillary services

Electricity market. The buying and selling of wholesale electricity on the grid by generators, retailers, and wholesale consumers, in advance or real-time, through a stock-market-like exchange

Full-load hours. The number of hours per year a plant operates at maximum output; related is "capacity factor," the annual average share of maximum output

Generation fleet. All of the dispatchable power plants connected to a grid

Grid operator. Keeps the lights on, operates transmission, and may run the electricity market. Usually called "independent system operator" (ISO) or "transmission system operator" (TSO)

Intermediate/peaking plants. Plants designed to run only part-time (intermediate/mid-merit) or only a few hours per day during peak hours (peaking)

Measures/innovations. The literature uses several different terms, including "measures," "options," "solutions," and "innovations," which are taken as roughly synonymous

Net load. Also called "residual load," denotes the required level of non-variable resources on a power system after subtracting out variable renewables generation

Pumped hydro. Hydropower with a lower and upper reservoir that acts as a battery when water is pumped uphill to the upper reservoir

Reserves. Power plants that are held back from generating, entirely or partly, to provide ancillary services when signaled by the grid operator

Resource adequacy. The planning process of ensuring enough resources are continuously available to keep a power system running reliably

Resources. Denotes sources of electricity, storage, responsive load, and other elements that combine to instantaneously serve the demand on a grid

Transmission/distribution. Transmission networks interconnect power plants and centers of power demand, feeding power to distribution networks that serve small areas and neighborhoods

Variable renewables. Renewables like wind and solar whose output is autonomously determined by the strength of wind and sun, usually not controllable by power grid

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