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Integrating Variable Renewable Energy: Challenges and Solutions

L. Bird, M. Milligan, and D. Lew
National Renewable Energy Laboratory

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Technical Report
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September 2013

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Introduction

In the United States, a number of utilities are adopting higher penetrations of renewables, driven in part by state policies. Today, wind power represents more than 10% of electricity generation in nine states and instantaneous penetrations of wind have reached levels of 25% to 55% of generation in some regions. While power systems have been designed to handle the variable nature of loads, the additional supply-side variability and uncertainty can pose new challenges for utilities and system operators. However, a variety of operational and technical solutions exist to help integrate higher penetrations of wind and solar generation. This article explores renewable energy integration challenges and mitigation strategies that have been implemented in the U.S. and internationally including: forecasting, demand response, flexible generation, larger balancing areas or balancing area cooperation, and operational practices such as fast scheduling and dispatch.

Wind and Solar Power Variability

Much of the variation in solar energy output during the course of the day and the year is highly predictable, because the movement of the sun is very well understood. An additional, less-predictable source of variability, however, is the presence of clouds that can pass over solar power plants and limit generation for short periods of time. Cloud cover can result in very rapid changes in the output of individual PV systems, but the impacts on the electric grid are minimized when solar projects are spread out geographically so that they are not impacted by clouds at the same time. In this way, the variability from a large number of systems is smoothed out. For large photovoltaic (PV) plants, cloud cover typically affects only a portion of the project at a given time while the clouds travel through the system.

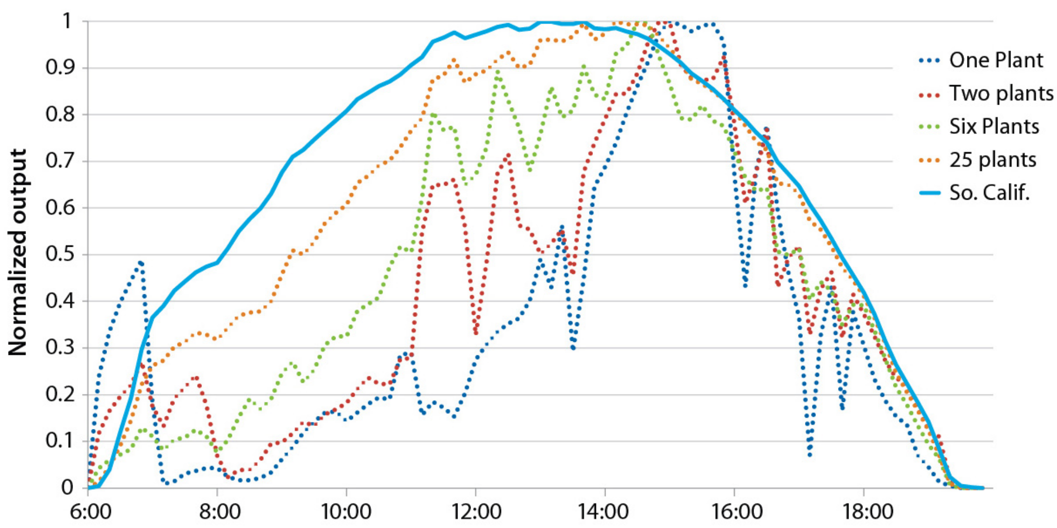

Figure 1. As the number of PV plants increases, their normalized, aggregate output becomes smoother. This is an example of normalized power output for increasing aggregation of PV in Southern California for a partly cloudy day for modeled PV plants in the Western Wind and Solar Integration Study Phase 2 (Lew et al. 2013).

Compared to solar, wind energy is less predictable, but still subject to daily and seasonal weather patterns. Often wind energy is more available in the winter or at nighttime, when the wind blows stronger. This can pose challenges in some instances if the output corresponds to lower load levels. A key difference in the variability of wind and solar power is that changes in wind generation typically occur more slowly, with large changes occurring during the course of hours as storm fronts move across a wind power plant. This is in contrast to the fast, second-to-second changes in solar power output that result from cloud cover.

Challenges Variable Renewable Energy Poses to the Grid

The uncertainty and variability of wind and solar generation can pose challenges for grid operators. Variability in generation sources can require additional actions to balance the system. Greater flexibility in the system may be needed to accommodate supply-side variability and the relationship to generation levels and loads. Sometimes wind generation will increase as load increases, but in cases in which renewable generation increases when load levels fall (or vice versa), additional actions to balance the system are needed. System operators need to ensure that they have sufficient resources to accommodate significant up or down ramps in wind generation to maintain system balance. Another challenge occurs when wind or solar generation is available during low load levels; in some cases, conventional generators may need to turn down to their minimum generation levels. Figure 2 provides an example of the flexibility needed for a high penetration of wind energy. Utilizing all of the wind energy would require conventional generators to meet the net load, which is defined as the demand minus the wind energy. The graph shows the load and net load for a sample week. There are periods when the net load changes, or ramps, more quickly than the load alone. Also, the remaining generators must be operated at a low output level (sometimes called "turndown") at night when there is a lot of wind power.

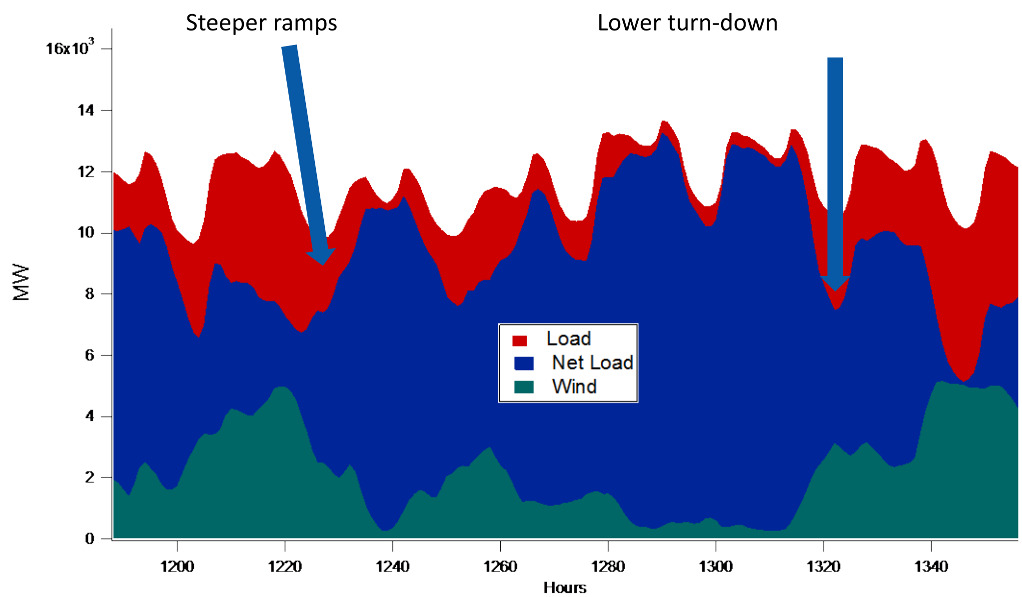

Figure 2. Wind energy requires additional flexibility from the remaining generators. Data from Minnesota 25% wind energy scenario.

In contrast to wind, solar generation is often more coincident with load. However, in regions with evening load peaks, loss of solar generation at sunset can exacerbate ramping needs to meet the evening demand. Extreme event analysis in the *Western Wind and Solar Integration Study Phase 2* (WWSIS-2), which examined renewable energy penetrations of up to 33%, showed that sunrise and sunset events dominate ramping needs. These events can be anticipated, however, because we know when the sun will rise and set each day. Because it is possible to plan for this aspect of solar power variability, increased operating reserve levels need to focus only on the unpredictable cloud variability, which is reduced by aggregation of geographically diverse solar power plants (as well as aggregation with wind and load variability). As a result, WWSIS-2 found that operating reserves were lower for the high solar scenario (25% solar) than the high wind scenario (25% wind) (Lew 2013).

Solar power that is connected to the distribution system has similar impacts as that connected to the bulk power system; however, there are differences. Transmission-level solar power plants provide real-time generation data to power system operators; whereas distributed solar power plants do not. That makes it difficult for a system operator to know whether an increase in net load is because of increasing demand or decreasing solar generation. Another difference is the way the solar generation reacts to faults or voltage excursions. Transmission-level solar power can be designed to maintain synchronization during faults of limited duration. However, current standards (Institute of Electrical and Electronics Engineers 1547) require distribution-level solar to quickly disconnect during these events. The result is that it may be more difficult to avoid or recover from some system disturbances.

Impacts to Fossil-Fueled Generators

The presence of additional wind and solar power on electric grids can cause coal or natural gas–fired plants to turn on and off more often or to modify their output levels more frequently to accommodate changes in variable generation. This type of cycling of fossil-fueled generators can result in an increase in wear-and-tear on the units and a decrease in efficiency, particularly from thermal stresses on equipment because of changes in output. Costs of cycling vary by type of generator. Generally, coal-fired thermal units have the highest cycling costs, although combined-cycle units and many combustion turbines, unless specifically designed to provide flexibility, can have significant costs as well. Hydropower turbines, internal combustion engines, and specially designed combustion turbines have the lowest cycling costs.

For coal plants in particular, the impacts can include increased damage to a boiler as a result of thermal stresses, decreased efficiency from running a plant at part load, increased fuel use from more starts, and difficulties in maintaining steam chemistry and NO_X control equipment (WGA 2012). Start-up costs are also influenced by how cold a unit is when it is being started. For example, hot starts (i.e., restarting a unit within 12 hours while a boiler and turbine are still relatively hot) have fewer impacts than cold starts (i.e., when a unit has been idle for three days and has cooled). A study by Xcel Energy found that for a 30-year-old 500-MW coal plant, costs ranged from $153,000 to $201,000 per cold start, whereas hot starts costs ranged from $82,000 to $110,000 (WGA 2012; Agan et al. 2008). Costs are specific to individual units, however, and can vary by vintage, design, operating history, maintenance history, and operating practice.

The impacts on fossil-fueled generation from high penetrations of wind and solar power (33% of generation) in the Western Interconnection of the United States were examined in detail by the WWSIS-2 study. It utilized cost data from hundreds of coal and natural gas plants regarding hot, warm, and cold starts, running at minimum generation levels, and ramping. These costs were used in a production cost model to optimize commitment and dispatch decisions. The study found that high penetrations of wind and solar power lead to cycling costs of $0.47/MWh to $1.28/MWh per fossil-fueled generator, on average. High penetrations of wind- and solar-induced cycling costs $35 million/year to $157 million/year across the West, while displacing fuel costs saved approximately $7 billion (Lew et al. 2013).

Cycling can also impact emissions from fossil-fueled generators because plants are run at part loads, ramped, and started more frequently. Although wind and solar power displace substantial emissions by reducing fossil-fuel use for electricity generation, how much the avoided emissions are eroded as a result of cycling of fossil-fueled plant operations has been questioned. Cycling of plants can lead to increases or decreases in emissions of CO_2, NO_X, and SO_2 from fossil-fueled generators, depending on the plant type and wind/solar power mix. The WWSIS-2 study found that cycling had a negligible impact on expected CO_2 emission reductions, improved NO_X emission reductions by approximately 1% to 2%, and worsened SO_2 emissions by approximately 2% to 5%. In the high wind and solar penetration scenarios SO2 emissions were reduced by 14% to 24% when cycling was accounted (Lew et al. 2013).

Addressing Integration Challenges

A variety of options are available to address integration challenges. Key considerations in selecting methods to address the variability and uncertainty of the renewable generation are the cost-effectiveness of the method and the characteristics of the existing grid system. Grid infrastructure, operational practices, the generation fleet, and regulatory structure all impact the types of solutions that are most economic and viable. Generally, systems need additional flexibility to be able to accommodate the additional variability of renewables. Flexibility can be achieved through institutional changes, operational practices, storage, demand-side flexibility, flexible generators, and other mechanisms. Several of these are discussed below, with an emphasis on their benefits, where they have been implemented, and effectiveness in addressing integration challenges. Many have been adopted because they reduce power system costs independent of variable renewable generation.

Advanced Forecasting

Wind and solar power forecasting can help reduce the uncertainty of variable renewable generation. The use of forecasts helps grid operators more efficiently commit or de-commit generators to accommodate changes in wind and solar generation and prepare for extreme events in which renewable generation is unusually high or low. Forecasts can help reduce the amount of operating reserves needed for the system, reducing costs of balancing the system. California Independent System Operator (CAISO) was the first to implement forecasting in 2004, and today it is well established and used in all independent system operators (ISOs). In the Western United States, approximately a dozen balancing authority areas, which encompass 80% of wind capacity, use forecasting (WGA 2012).

Improvements have been made in recent years toward reducing mean average forecast errors. For example, Xcel Energy reduced its mean average errors from 15.7% to 12.2% between 2009 and 2010, resulting in a savings of $2.5 million (WGA 2012). Today, forecast errors typically range from 3% to 6% of rated capacity one hour ahead and 6% to 8% a day ahead on a regional basis (as opposed to for a single plant). In comparison, errors for forecasting load typically range from 1% to 3% day-ahead (Lew et al. 2011). Day-ahead forecasts can be used to make day-ahead unit commitment decisions and thus drive operational efficiency and cost savings. Short-term forecasts can be used to determine the need for a quick-start generator, demand response, or other mitigating option and thus drive reliability.

Solar forecasting is emerging, although not widely used today. Clouds are the primary cause of variability for solar generation, aside from the predictable changes during the course of the day and throughout the year. The ability to accurately forecast solar power depends on the character of cloud cover, including the amount of water or ice in clouds and aerosols. To assess near-term impacts of approaching clouds on solar generation, sky imagers can be used. To predict impacts during the next few hours, satellite images can be used to assess the direction and speed of approaching clouds. For longer periods, weather models can be used to determine how clouds may form and change (WGA, 2012).

Operational Practices—Fast Dispatch and Larger Balancing Authority Areas

Fast dispatch helps manage the variability of renewable generation because it reduces the need for regulating resources, improves efficiency, and provides access to a broader set of resources to balance the system. When generators have fixed schedules for longer periods, such as an hour—which has been the standard practice in much of the West historically—generators are committed to their set schedules and not available to help balance the system in the case of schedule deviations. With faster dispatch, load and generation levels can be more closely matched, reducing the need for more expensive regulating reserves. This enables more efficient balancing and utilization of the most economical resources within the system.

Five-minute dispatch is currently the norm in ISOs throughout the country, serving over 2/3 of the national load. Five minute scheduling was adopted because it reduces power system operating costs, not to enable renewable generation integration. Five minute scheduling has helped reduce regulation requirements to below 1% of peak daily load in many ISO/RTOs. Studies have shown that integration costs are lower in areas with faster dispatch. For example, integration costs have ranged from $0/MWh to$4.40/MWh in areas with five-minute dispatch, compared to $7/MWh to 8/MWh in areas with hourly dispatch (WGA 2012). Integration studies have also demonstrated savings from faster dispatch and scheduling. For example, the *Western Wind and Solar Integration Study Phase 1* found that the use of subhourly scheduling cut in half the amount of fast maneuvering required by combined-cycle plants. It also found that hourly scheduling had a greater impact on regulation requirements than the variability introduced by wind and solar power in the scenarios studied.

The effects of size and dispatch speed are shown in Figure 3. The three boxes represent different aggregation levels of the Western Interconnection that range from the existing 37 balancing authority areas to the entire Western footprint. Within each box, the impact of dispatch frequency, ranging from 10 minutes to 60 minutes, is shown. In addition, alternative forecast horizons are analyzed. Thus “30-10” represents a 30-minute dispatch time step with a 10-minute forecast horizon, and “10-10” represents a 10-minute dispatch with a 10-minute forecast horizon.

The graph shows a reduction in required regulating reserves from nearly 9,000 MW to slightly more than 1,000 MW in the most extreme cases (Milligan et al. 2011).

In June 2012, the Federal Energy Regulatory Commission (FERC) issued Order 764 regarding the integration of variable generation. The final rule requires transmission providers to allow 15-minute scheduling of transmission service to facilitate faster dispatch and interchange schedule changes. The order also calls for new variable generators to provide forced outage and meteorological data to transmission providers if it is needed by the system operator to forecast power production.

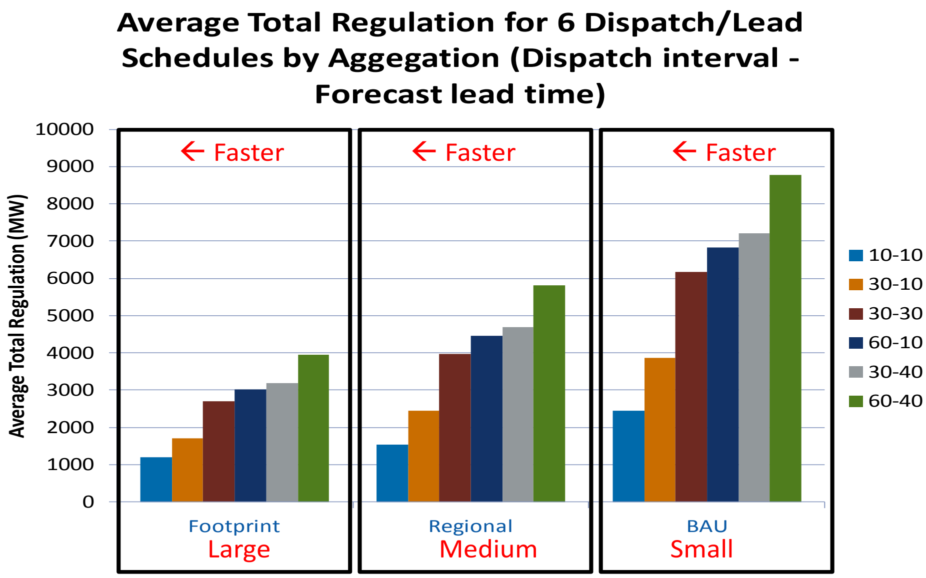

Figure 3. The size of the balancing authority area and increasing frequency of dispatch can reduce regulating reserve (Milligan et al. 2011).

CAISO and PacifiCorp have announced plans, approved by FERC in July 2013, to implement an energy imbalance market (EIM) with 5-minute dispatch by October 2014. An EIM is a centralized market that facilitates fast dispatch of least-cost generation across balancing authority areas to address energy imbalances, or differences between scheduled and actual energy. The CAISO/PacifiCorp proposal is expected to reduce costs by providing greater efficiency in balancing by reducing the total system variability (CAISO and PacifiCorp imbalances partially cancel). It is also expected to enable access to a broader pool of balancing resources across the balancing authority areas, reduce wind energy curtailments, and reduce the need to hold flexibility reserves. Benefits of an EIM are estimated to be larger with broader participation. An earlier study by Energy and Environmental Economics, Inc. (E3) found that an EIM implemented throughout the West would reduce costs by $50 million in 2006 and would lead to $141 million in savings by 2020 by removing barriers to trade and savings from reduced flexibility reserves (WGA 2012). A study by NREL found that full regional participation in an EIM would result in savings of $297 million, and partial implementation would lead to $276 million in savings (Milligan et al. 2013).

Reserves Management

Reserve management practices can be modified to help address the variability of wind and solar power. Practices that reduce overall reserve requirements can lead to substantial cost savings. Potential tools for managing variability include placing limits on wind energy ramps to reduce the need for reserves and enable variable renewables to provide reserves or other ancillary services.

Limiting up ramps is another potential tool for managing variability. Because reserve levels are set to address relatively low-probability, large changes in wind output, modest limits on wind generation can significantly reduce the need for balancing reserves, yielding cost savings. Ramp events that affect plants across a balancing authority area result from large-scale weather events that can be more easily predicted than local weather events. By imposing ramping limits on wind generators when large-scale weather events are forecasted, balancing reserve requirements may be significantly reduced. Ramp rate controls are a relatively low-cost tool for minimizing system impacts; the primary costs are associated with the curtailed generation and the communications and control equipment. Ramp rate controls on renewable generators have been implemented in the Electric Reliability Council of Texas (ERCOT), Ireland, Germany, and Hawaii (WGA 2012).

Another option is to design incentives so that wind and solar power plants can provide regulation, inertia, or other ancillary services if it is economical to do so. Wind and solar plants are especially good at providing down reserves at very low cost. The provision of ancillary services up reserves from wind or solar power plants will necessarily reduce energy production—as it does for conventional plants that provide those services—but incentives such as the production tax credit does not recognize the potential value of wind-provided ancillary services.

Market Design—Flexibility Markets

Wind and solar energy have near-zero marginal cost. Therefore, when they are part of a market dispatch, overall energy prices will decline. Although this may be an advantage for consumers, there are questions about the sustainability of this type of market because some generators may earn insufficient revenue to cover both their variable and fixed costs. This has led to significant interest in capacity markets. For example, the FERC is convened a technical conference on this topic in September 2013.

Another concern is whether energy markets, even with fast economic dispatch at 5-minute time steps, provides sufficient incentives to generators to perform in a flexible manner. This issue is not settled, but the CAISO has developed a ramping product called “flexi-ramp” that is intended to supplement the energy market. The objective is to ensure sufficient ramping capability, and this may require changing the dispatch set points of some generators to ensure this flexibility is available in real-time if it is needed. Midcontinent Independent System Operator (MISO) has developed a program called “dispatchable intermittent resources,” or DIR, which utilizes a multi-period look-ahead process that helps to anticipate the load and wind (and solar) power levels on a longer time horizon to help optimize the way generation is dispatched. However, the need for a new ancillary service is not universally recognized. For example, ERCOT does not have such a product, and, despite having in excess of 10,000 MW of wind on its system, is not developing a product like flexi-ramp at this time.

Demand Response

Demand-side flexibility can also aide in the integration of variable renewable generation, particularly in cases of fast ramps or extreme events. Demand response can be used to supply reserves and ancillary services as well as peak reduction. ERCOT, for example, obtains half of its spinning reserves from demand response. The use of demand response to balance the system during infrequent events in which there is substantial under- or oversupply of renewable generation can lead to cost savings compared to continually maintaining additional reserves. For example, the Western Wind and Solar Integration Study estimated cost savings of $310,000 to $450,000 per MW annually for the high wind penetration case when using demand response to balance the system for the small number of hours that extreme events occurred during the course of the year rather than maintaining increased spinning reserves for the entire year (GE 2010). Demand response could be considered part of a portfolio of measures that can complement deployment of higher penetrations of variable renewable energy.

Flexible Generation Sources

Flexibility to accommodate wind and solar power can also be achieved through the use of flexible generating sources. The flexibility of generation sources can be gauged by their ramp rates, output control range, response accuracy as well as minimum run times and off times, start-up time, cycling cost, and minimum generation level. Some forms of flexibility are inherent to particular types of generators, whereas others can be affected by the plant design or the way in which it is operated. Increasing the flexibility of existing plants can require capital outlays as well as impacts to plant efficiency and maintenance costs.

Generally, natural gas combustion turbines, hydropower plants, and internal combustion engines are among the most flexible generators if not subject to other constraints, whereas coal and nuclear base-load units are among the least flexible. Thermal steam plants have a substantial amount of thermal inertia in the boiler that limits their ability to ramp up or down quickly. Most coal-fired plants in the United States were designed to operate at relatively constant, high levels to provide base-load generation. Older plants have generally been designed to have minimum operating levels of about 45% to 50% of their rated capacity, whereas newer facilities often have minimum load levels of approximately 35%. Combined-cycle natural gas plants are generally able to ramp faster than coal plants, but are not as nimble as combustion turbines. Many older combined-cycle units were often designed to optimize efficiency, not for flexibility, but newer units generally have increased flexibility and minimum generation levels of approximately 35%. In general, the flexibility of natural gas–fired thermal units is constrained by time needed to warm up and for the heat-recovery steam generator to meet required conditions, as well as limits on pressure and temperature (WGA, 2012; Puga 2010). Utility scale internal combustion engine driven generators are now often designed for very quick start (one minute to synchronization and five minutes to full load) with zero cycling cost.

Flexibility in the generation fleet can be achieved through modifications to existing units or through the addition of new flexible units. Some existing generators can be modified to increase flexibility by increasing ramp rates, lowering minimum generation levels, speeding up start-up, or lowering wear-and-tear costs to enable them to better perform load following. Wear-and-tear costs can be reduced through preventative or corrective maintenance, changing operating procedures, and upgrading equipment (WGA 2012).

Relatively new types of generators have been developed that have relatively flat efficiency curves, can start and stop quickly and at very low cost, and can ramp quickly. Some of these units are aero-derivative gas turbines, which utilize jet aircraft engine technology. Other types of flexible generators are reciprocating engines, which consist of multiple small generators connected in parallel. Although each engine, which often runs on natural gas, can cycle relatively efficiency, the existence of multiple engines provides a scalable ramping capability—e.g., if one unit can ramp from 0% to 100% of output in 5 minutes, then the entire plant can match this performance because the plant is made up of multiple generators.

Obtaining a generation fleet with the needed flexibility attributes is a necessary, but not sufficient, condition for efficient integration. Markets and operational process must allow the system operator to access this flexibility. For example, under a paradigm of hourly dispatch and interchange scheduling, an operator may not have the ability to access the fast ramping capability that may physically exist. Recognition of this possibility, and proactive revision of markets or other procedures, will improve system performance and improve integration in the bulk power system.

Conclusions

Many options exist for addressing challenges associated with variability and uncertainty of renewable energy generation. All electric grids are different and the optimal solutions for addressing integration vary accordingly. The least-cost options available to individual grids depend on the overall flexibility of the grid because of the generation mix (including the renewable energy penetration), regulatory structure, presence or absence of markets, operational practices, and institutional structures. With more utilities and system operators in the United States and internationally integrating higher penetrations of renewables, a variety of tools and operational practices have been implemented.

Other potential solutions require additional study and implementation experience. For example, markets could be designed to elicit needed flexibility, both in real time and to incent investment in the desired level of flexibility, but the most effective mechanisms to do so are not yet well understood. In addition, alternative methods of managing reserves may be possible and could result in improved efficiency with higher penetrations of renewables. Finally, a better understanding of the least-cost mix of generation sources with higher levels of wind and solar energy and a better understanding of the cost of various flexibility options and metrics for assessing flexibility could be useful for identifying and evaluating solutions.

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