Chapter 3: Integration of Variable Energy Resources

In this chapter, we discuss the challenges of operating the grid with high penetrations of wind and solar generation, commonly referred to as "variable energy resources" (VERs). We also present a variety of changes to system operation and planning that can help in meeting these challenges. The chapter provides background on ongoing industry and government efforts to integrate and increase the penetration of VERs, as well as context for later chapters. The topics described in this chapter are of primary interest to industry decision makers.

Section 3.1 describes the basic technical and economic characteristics of VERs and introduces the challenges for the power system derived from the variability and uncertainty of these generation sources. This is followed in Section 3.2 by a discussion of the impact that high penetrations of VERs could have on system operating reserve requirements and several ways to limit system operation cost increases. These include improving VER forecasts and situational awareness, moving generation scheduling decisions closer to real time, and expanding cooperation among neighboring balancing areas. We find that these operational changes will become increasingly important as VER penetrations grow.

Section 3.3 discusses the impact of high VER penetrations on the future well-adapted generation mix and the need to ensure adequate system flexibility. We describe sources of system flexibility, including conventional generation technologies and potential new resources, such as demand response and energy storage.

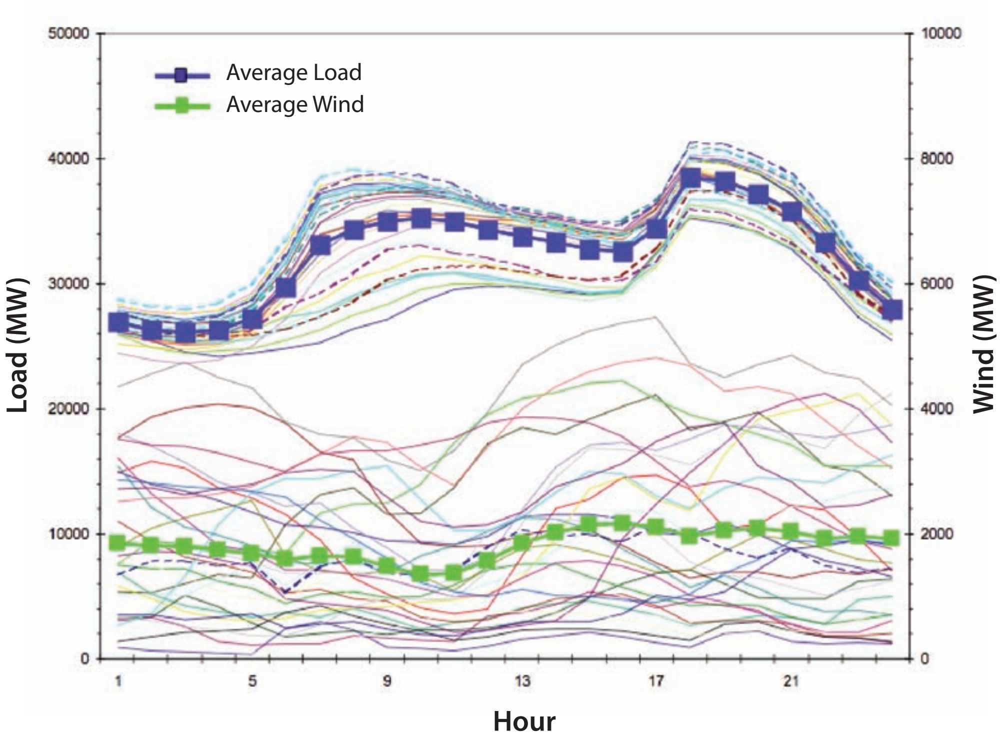
Section 3.4 discusses the critical role of interconnection standards in assuring that reliability is maintained as the penetration of VERs increases. These standards, for both VERs and conventional generation technologies, will need to adapt to the increasing role of VERs. It is particularly important that they be structured in response to anticipated rather than existing conditions.

Section 3.5 gives our conclusions and recommendations. First, we recommend more widespread sharing of granular meteorological data measured at VER sites. Second, we recommend several changes to system operations that could facilitate the integration of VERs in many regions. Finally, we recommend that mechanisms that provide incentives for investment in flexible generation and for operating flexibly be devised and deployed in regions with growing VER penetrations.

Most projections of U.S. electricity production show a substantial increase from wind and solar generation, which are receiving a strong push from state and federal policy through subsidies and renewable portfolio standards. For example, the U.S. Energy Information Administration (EIA) expects renewable sources to constitute 25% of the increase in total generating capacity across the electric power sector between 2010 and 2030.[1]

Commonly referred to as "variable energy resources" (VER), wind and solar power generators are known to be *variable* and *uncertain* because they are subject to only limited control and the energy they produce is less predictable compared to energy from conventional technologies. Variability and uncertainty are familiar concepts in power systems. Through decades of experience, system operators have developed approaches to cope with variability and uncertainty that stem, for instance, from changing demand levels and failures of generation units. But wind and solar generation as new sources of variability and uncertainty present challenges to the operation of the power system.

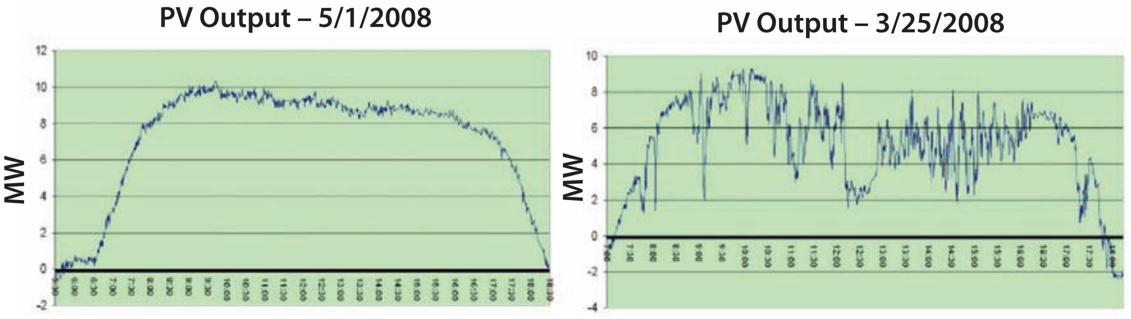
Figure 3.1 Daily Load and Wind Generation Profiles in the California System Compared to Average Profiles for the Month of January 2002



Note: This figure compares daily wind generation and load profiles in California in January 2002. The colored lines in the upper portion of the plot illustrate each individual day's load profile while the lines in the lower half of the plot illustrate each individual day's wind generation profile. The thicker lines indicate the monthly average profiles for load and wind.

Source: GE Energy Consulting, "Intermittency Analysis Project: Appendix B, Impact of Intermittent Generation on Operation of California Power Grid" (Sacramento, CA: California Energy Commission, 2007).

Figure 3.2 Nevada Solar Photovoltaic (PV) Plant Output on a Sunny Day (Left) and a Partly Cloudy Day (Right) in 2008



Source: North American Electric Reliability Corporation, *Accommodating High Levels of Variable Generation* (Princeton, NJ, 2009).

3.1 CHARACTERISTICS OF VARIABLE ENERGY RESOURCES

Figure 3.1, a plot of California's wind generation and its relation to demand, illustrates some of the challenges associated with wind generation. As seen here, wind output can change more rapidly and over a wider range than demand, and it does not conform to daily cyclic patterns. An inverse correlation is sometimes observed in which wind resources on average become most abundant during hours of limited demand at night.[2]

Compared to wind, solar outputs are generally considerably more cyclic and better correlated with load, typically achieving maximum output a few hours before peak demand. However, especially at the individual plant level, solar generation without storage can also produce outputs that are considerably more variable and less predictable than wind. As illustrated in Figure 3.2, individual solar photovoltaic (PV) plants under cloud cover have been observed to vary their outputs by as much as 90% over the course of seconds.

When wind variations or passing clouds result in changes in output, dispatchable generators or loads must make corresponding changes in an effort to balance generation with load over a specific geographic area known as a "balancing region." Larger balancing regions have a greater diversity in VER resource availability and load over wide regions, smoothing out the effects of minute-by-minute variability. Adjacent smaller balancing areas can reap the full benefits of resource diversity by consolidating or cooperating with each other.

Beyond variability, the high uncertainty associated with VER outputs also can complicate existing balancing processes and is often cited as the main source of costs of integrating VER generators into the grid.[3] Since day-to-day wind speeds and cloud cover are significantly less certain than the load forecast, systems with high penetrations of VERs typically must commit more reserve generation than those with low penetrations, which drives an increase in costs. Exacerbating these concerns, large-scale weather events, such as wind storms and wide-area cloud cover, create challenging operational situations known as "ramp events" that are characterized by a significant portion of the VER fleet ramping up or down in unison over a period of minutes to hours. Because ramp events are often difficult to forecast ahead of time, additional reserve generation (or demand response) must be ready to increase production (or decrease load) to meet the load if the VERs ramp down or decrease production if the VERs ramp up. Finally, the absence or very limited presence of the VERs during extended periods of time (e.g. several consecutive days) also can result in operation challenges. The power system must have enough response capacity, from interconnections, demand response, storage, and backup supply to maintain reliability standards under these worst-case conditions.

The power system must have enough response capacity, from interconnections, demand response, storage, and backup supply to maintain reliability standards.

All the operational adaptations to accommodate VERs require more flexible power systems, incurring operational costs. Fossil fuel plants must bear the expense of additional start-ups and shut-downs, as well as operation at output levels distant from points of optimal fuel efficiency and air pollution control. In addition, more frequent start-ups, shut-downs, and ramping can increase mechanical stress on generation plants, potentially resulting in higher maintenance costs and reduced life.[4] Providing these services at minimum cost while maintaining reliability and system stability requires careful planning of investments, such as the timely addition of dispatchable plants with fast ramping capability.

Beyond the variability and uncertainty of their outputs, wind and solar generation have control and electrical characteristics that are different from those of conventional

BOX 3.1 ALLOCATION OF SYSTEM OPERATING COSTS

The allocation of the increase in system operating costs that results from the introduction of large penetrations of variable energy resources (VER) is a subject of current debate. Historically, the cost of reserves required to reliably operate power systems has been allocated to all end consumers. In a November 2010 Notice of Proposed Rulemaking, the Federal Energy Regulatory Commission (FERC) suggested that VERs be made partly or wholly responsible for the additional costs that they cause.[5]

As with any zero-sum game, it will be difficult to arrive at a mutually agreeable solution, particularly now that the incurred costs are becoming significant. This is exemplified by the responses to the notice.

The respondents to the notice agree that such a cost-allocation scheme for operating reserves will be hard to realize in practice. Regardless, some suggest possible implementations. FERC proposes adding a special ancillary services rate to the transmission access tariffs for VERs.[6] The Federal Trade Commission suggests that each VER plant purchase option contracts on flexible resources that can provide reserves.[7] The Bonneville Power Administration is exploring the possibility of allowing wind generators to pay the cost of their variability by self-supplying the extra electricity to correct any imbalance.[8] This last scheme is in accordance with the design of balancing markets already in place in some European countries.

synchronous generators. Due to their very low penetrations, to date VERs have been required to meet few performance standards in the U.S. As VER penetrations grow, it will become increasingly important that interconnection standards require all generators, including VERs, to play an active role in helping to maintain system stability and reliability under the new anticipated conditions. Because retrofitting generation is typically expensive, it is particularly important that interconnection requirements for all generation technologies, both VER and conventional, be designed for anticipated rather than existing conditions.

VERs historically have affected the U.S. bulk power system very little because they have accounted for only a small fraction of energy supply. However, with significant growth, these policy-backed technologies will require changes to how systems are planned, operated, and controlled. This chapter explores these challenges of system adaptation and the ways that grid management and operation can help minimize the potential grid-related costs of VER expansion. The allocation of the increase in system operating costs that results from high penetration of VERs is also a subject of current debate, as described in Box 3.1.

All the adaptations described in this chapter have been identified and studied in the wind integration literature, and many have been implemented in other countries and in parts of the U.S.[9] Our focus is on wind farms and large-scale PV or concentrated solar thermal installations without storage. We address the implications of large-scale VERs for planning and building transmission systems in Chapter 4, and we discuss the distribution system challenges of distributed generation, usually residential and commercial rooftop PV installations, in Chapter 5.

3.2 VARIABLE ENERGY RESOURCES AND THE COST OF RESERVES

As explained in Chapter 2, generators are initially dispatched according to unit commitment schedules made one day in advance. The unit commitment or day-ahead market process determines which generators will come online or go off-line at various times during the following day. Vertically integrated utilities attempt to minimize the cost of meeting load, subject to transmission line capacity limits and other security constraints, by dispatching generators with lower marginal operating costs before those with higher costs. Where there are organized wholesale markets, system operators utilize generators' bids instead of actual costs in determining how units are dispatched. This process, discussed in Appendix B, is known as "security-constrained economic dispatch." Either by central decision-making or through markets, provisions must be made for the supply of operating reserves and balancing services.

Operators make these scheduling decisions under a level of uncertainty. Since forecasts are never perfect one day in advance, on the day of dispatch, a committed generator may not be needed, or an uncommitted unit might be needed. The committed generators may fail to meet their dispatch schedule due to unforeseen equipment failures or other contingencies, necessitating the dispatch of reserves. Generators and demand response can provide these operating reserves.

Operating reserves are categorized according to the types of events to which they are designed to respond and to the speed, timescale, and direction (up or down) of response expected. In the context of VER integration, five categories of reserves are significant, listed in order of response time:[i]

- Frequency Response Reserves (milliseconds to seconds): The fastest reserves are used to respond to such contingencies as the loss of a generator or transmission line. They are activated automatically on individual generators and at control centers, and are rarely explicitly dispatched by the operator.

Wind integration studies and experience have shown that the additional variability and uncertainty associated with higher penetrations of wind will increase operating reserve requirements.

- Regulating Reserves (seconds): These are used during normal operation to maintain the balance between supply and demand due to random changes in generation or load. They are dispatched by the operator in times that are faster than the clearing periods of energy markets.
- Ramping Reserve (minutes to hours): These reserves respond to ramp events that occur over periods of minutes to hours. They can ramp their outputs either up or down and are designed to cover challenging operational conditions, such as wind forecast errors.
- Load-following Reserves (minutes): These are dispatched during normal operations by the operator to maintain the balance between supply and demand due to cyclical (e.g. daily, weekly) changes in demand or generation, on a slower timescale than regulating reserves.
- Supplemental Reserves (tens of minutes to hours): The slowest form of reserves, these resources are deployed during contingencies alongside faster reserves. They are designed to slowly ramp up and replace faster reserves, which are then available to address future contingency events.

Wind integration studies and experience have shown that the additional variability and uncertainty associated with higher penetrations of wind will increase operating reserve requirements.[10] The Federal Energy Regulatory Commission (FERC) has cited this increase as one of the most important sources of cost

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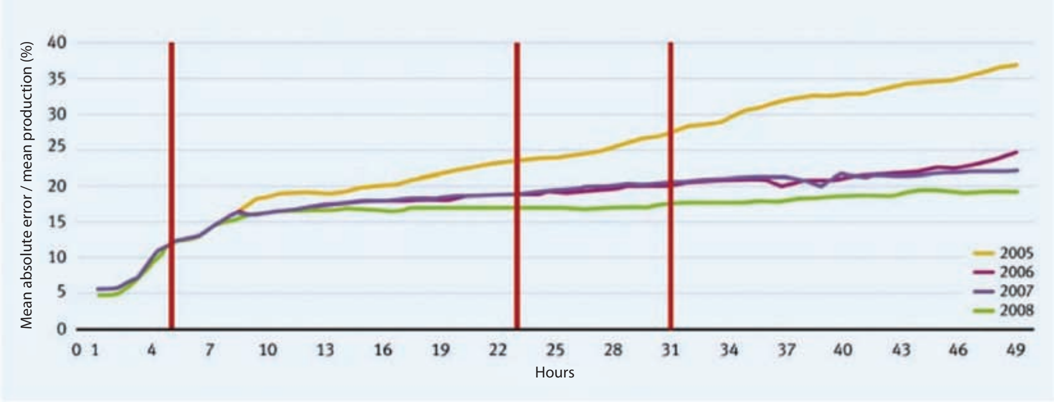
[i] A variety of terms are commonly used to describe each type of reserve in different systems and different countries.[11]

Figure 3.3 The Evolution of Forecasting Errors versus Lead Time, 2005–2008



Note: The red bars mark the typical time when generation schedules become final and binding for different markets.

Source: Eurelectric, *Integrating Intermittent Renewables Sources into the EU Electricity System by 2020: Challenges and Solutions* (Brussels, Belgium, 2010).

increases from the integration of VERs in the U.S.[12] Understanding the full impact of this increase in operating reserves on costs will require a closer examination of how VERs affect each category of reserves.

Regulating Reserves. The uncertainty and the variability of VERs can create fluctuations in production on the order of minutes. Accommodating these fluctuations may require a modest increase in fast-responding regulating reserves required for normal operations.

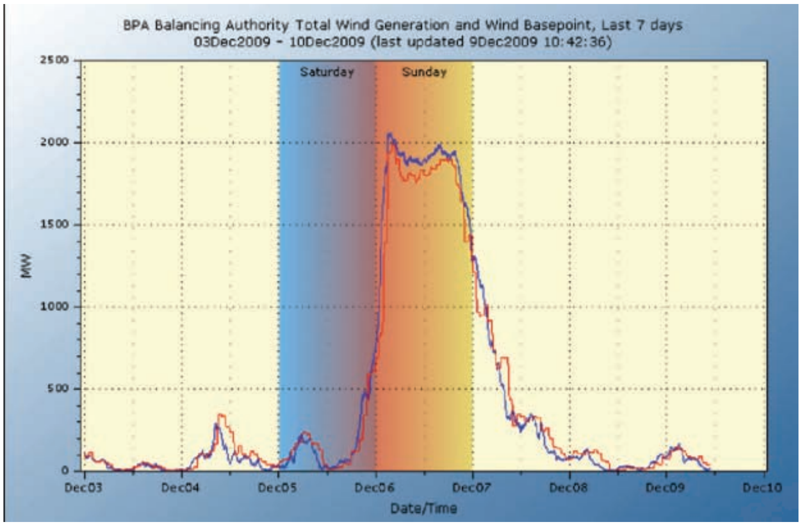
Frequency Response and **Supplemental Reserves.** All major international studies have concluded that large VER penetrations do not significantly increase the risks for traditional contingencies.[ii] Large penetrations are expected to be comprised of many small plants on the order of 1–5 megawatts (MW) over wide geographic areas, and it is highly unlikely that many of these plants simultaneously would stop producing.[13] Even when VERs do simultaneously ramp down, they typically take minutes to hours, which is much slower than traditional contingencies, such as a large generation plant tripping off-line, that occur in seconds.[iii]

Ramping and **Load-following Reserves.** Ramping and load-following reserves are primarily used to counteract VER forecast errors in the day-ahead scheduling of plants. At this timescale, wind forecasts have an average error of 15%–30% mean absolute error of production, despite the significant improvements in wind forecasting over the past decade, as illustrated in Figure 3.3.[14] For comparison, day-ahead load forecast errors are typically below 1% mean average error of production.[15] As a result, operators must conservatively operate the system assuming that the actual VER production could be at least 20% lower

[ii] These studies assume that requirements for fault tolerance are present in grid interconnection standards. This issue is described further in Section 3.4.

[iii] An exception is the occurrence of wind exceeding maximum allowable speed and causing multiple turbines to shut down simultaneously.

Figure 3.4 Ramp-up and Ramp-down Events in the Bonneville Power Administration Region



Note: The red line indicates the final scheduled wind generation (economic dispatch base point). The blue line indicates actual wind generation.

Source: North American Energy Reliability Corporation, *NERC IVGTF Task 2.4 Report: Operation Practices, Procedures, and Tools* (Princeton, NJ, 2011).

than forecasted, requiring large quantities of reserves, which are then dispatched throughout the day if forecast errors become apparent.

Load-following and ramping reserves also are used to hedge the risk of VER ramp events. Though not a traditional contingency, ramp events can present a significant operating concern. The risk of ramp events in most cases comes from the uncertainty of when they will occur and how long they will last. Indeed, predictions of ramp event occurrence and timing are often difficult and can result in large and sudden forecast errors that deplete reserves that are on-line in a time too short to activate reserves that are fully off-line.[16]

Figure 3.4 shows two ramp events that depleted reserves procured by the Bonneville Power Administration in December 2009. Wind output ramped up sharply in the late hours of December 6 and the early morning of December 7 to nearly 2,000 MW—a substantial portion of the agency's total wind generation capacity (around 3,000 MW at the time). BPA deployed more than 90 percent of its reserves as the wind ramped up and BPA had to curtail some wind generation by issuing generation limits to wind generators, in order to avoid violating its reserve requirements. Wind output then ramped down to zero through the night hours of December 7 and the morning hours of December 8. This down ramp resulted in BPA depleting 100 percent of its reserves and prompted BPA to curtail transmission schedules for wind generators. Uncertainty in both the size and duration of ramp events complicates operator responses.

In the remainder of this section, we discuss a set of tools that can serve to reduce the cost of reserves associated with VERs. Many of these tools will allow the electricity market to better address the impending need for flexible resources: if the electricity commodity market is liquid and a strong price signal exists, the fastest flexible resources will be able to offer their services closer to the time when they are actually needed. This allows the system to avoid locking in resources that it will not eventually need, and these can be freed for other uses.[17]

Improve Variable Energy Resource Forecasts and Situational Awareness

Improving the accuracy of VER power production forecasts is one of the most straightforward ways to reduce the impact of VERs on reserve requirements and thus system operating costs. Reducing day-ahead forecast errors lessens the risk of under committing generation, thus also diminishing the ramping reserves needed to hedge this risk. Reducing real-time forecast errors can increase the accuracy of the real-time dispatch schedule, diminishing the imbalances that must be corrected by regulating and load-following reserves.

Wind power generation forecasts used in power system operations typically are based on a combination of data from large-scale numerical weather prediction (NWP) models maintained by public meteorological agencies and meteorological and power production data measured at individual VER installations. NWP datasets are wide in regional scope and comprehensively describe many aspects related to the state of the atmosphere at a given time. However, due to the computational complexity of the models used to generate these datasets, they are typically refreshed slowly and have relatively poor spatial resolution. Improvements in the affordability and power of computational technologies have yielded significant advances in NWP models in recent years. In the U.S., the National Oceanic and Atmospheric Administration (NOAA) recently began updating NWP data every hour instead of every six hours, and the agency is developing further improvements.[18]

Local meteorological and power production measurements at individual VER installations are also an important input to VER forecasting models. These datasets are typically refreshed more often than the NWP data that NOAA provides and have higher spatial resolution. Individual VER owners and forecast vendors collect and use the data to produce power production forecasts. VER generators in some regions where independent system operators (ISOs) and regional transmission organizations (RTOs) exist are required to provide data to system operators for the purpose of forecasting. However, this is not universally the case.[19] System operators have indicated that accurate data from VERs are critical to generating accurate forecasts.[20] In a November 2010 Notice of Proposed Rulemaking, FERC proposed to mandate reporting of such data for the purpose of centralized forecasting in real time or near-real time by system operators in regions with significant penetrations of VERs.[21] Increased data sharing would improve power production forecasting, and is widely understood to be an important step in reducing the cost of VER integration. At the same time, increased data reporting and compliance monitoring will also result in increased costs, and these increases may exceed the benefits in regions that do not expect substantial penetrations of VERs. As of November 2011, a final rule had not been issued.

Local data from VERs are considered proprietary and confidential, and they are rarely shared beyond forecast vendors and system operators.[22] NOAA has cited limited access to wind data at wind turbine–hub height as a significant limitation to the prediction accuracy of current NWP models and has urged FERC to consider also mandating VERs to share local meteorological measurements with NOAA.[23] Of course, protections would need to be in place for commercially sensitive information.

Such confidentiality arrangements already exist between NOAA and many airline companies. NOAA also has been working to form voluntary data-sharing partnerships with industry stakeholders and has embarked on efforts to better quantify the potential benefits that increased data access may yield.[24]

FINDING

Greater sharing of meteorological data would improve wind forecast accuracy in regions with high penetrations of VERs.

Beyond improving power production forecasts, developing and improving tools for ramp-event prediction also can reduce the impact of VERs on system operating costs. Unlike a conventional VER forecasting system, a forecasting system for ramp events has the goal of identifying specific meteorological conditions that could translate to high risks for ramp events. System operators can take specific preventative actions to protect system reliability and timelier, less resource-intensive decisions to address potential ramp events when forecasting tools observe these conditions.[25] A recent review of ramp event-forecasting methodologies by Argonne National Laboratory indicates that ramp-event prediction remains a relatively novel problem for meteorologists and reports that existing forecasts tend to be “unreliable and of low accuracy.”[26] Fortunately, ramp-forecast skill is rapidly increasing, driven both by public research institutes as well as private wind-forecasting companies. Like the case for improving regular VER forecasts, it has been suggested that providing forecasters with greater access to meteorological data would improve forecasts.[27]

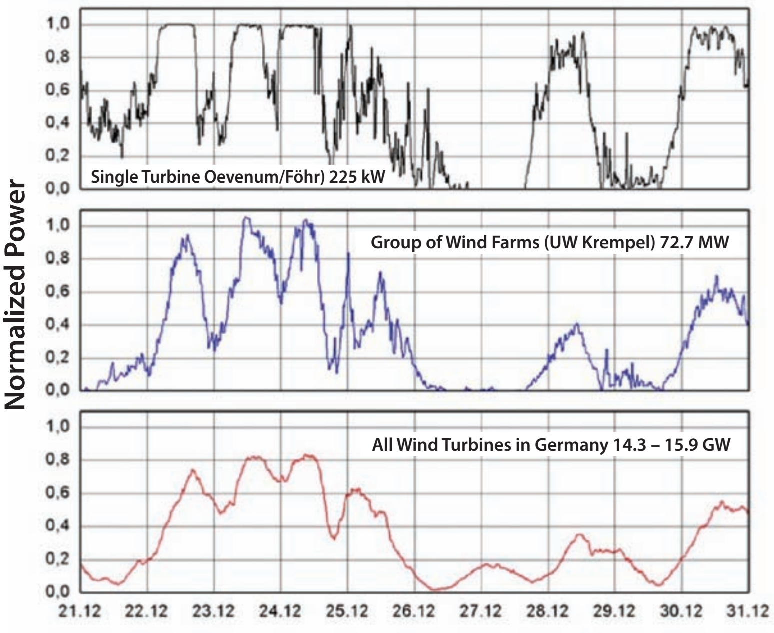
Reducing the potential impacts of VER ramp events also will require deploying technology to increase operators’ situational awareness of system conditions. Some of these tools, such as phasor measurement units, are described in Chapter 2. Finally, data analysis and visualization tools that effectively aid operators’ decision-making will be important. Many system operators in the U.S. with growing penetrations of VERs are in the process of developing programs to aid in identifying and responding to the risks of VER ramp events.[28]

Make More Frequent Decisions Closer to Real Time

As discussed earlier and illustrated in Figure 3.3, the accuracy of wind forecasts increases appreciably closer to real time. There are two primary mechanisms for improving scheduling practices to take advantage of this phenomenon: shorter gate-closure periods (the time before the operating period when generation schedules become final and binding) and shorter commitment periods (the length of time the generator is committed to produce). Historically, both measures have been deployed in various regions to counter the variability and uncertainty of loads. Recent research and operating experiences from around the world have shown that they also can yield potentially large benefits in accommodating large penetrations of VERs.[29]

Moving gate closure nearer to the corresponding operating period results in more accurate forecasts, as shown in Figure 3.3, and better-performing schedules in systems with a significant penetration of VERs. Various mechanisms already exist to achieve shorter gate-closure periods due to the large benefits that are available even in systems without VERs. Notably in the U.S., most ISO/RTO regions operate real-time markets that layer on top of day-ahead markets. A generator with an obligation from the day-ahead market may still buy or sell in shorter-term markets that are closer to real time. Intraday markets have been developed on top of power exchange markets, initially in Spain and then in other countries, and their use has been mandated recently within the European Union. While these markets differ by name and implementation, in practice they all shorten the gate-closure period.

Figure 3.5 Individual and Aggregated Power Outputs of Wind Turbines



Source: Copyright © Fraunhofer IWES, Germany; Institute for Solar Energy Technology, Wind Energy Report Germany 2005 (Kassel, Germany, 2005); H. Holtinnen et al., Design and Operation of Power Systems with Large Amounts of Wind Power: Final Report, Phase One 2006–2008, research note 2493 (Espoo, Finland: VTT, 2009).

Shorter operating periods allow schedules to roll over more smoothly and forecasters to refresh their forecasts more often, which reduces the magnitude of forecast errors and associated scheduling errors. With increasing penetrations of VERs, shorter operating periods also could align market operations more closely with the predominant variations associated with wind, which most often vary over tens of minutes.[30]

In the U.S., most RTO/ISO regions already administer wholesale energy markets with short gate-closure periods and five- to fifteen-minute scheduling and dispatch. For the Southeast and the portions of the Western Interconnection outside the California ISO, however, the electric grid is managed by transmission owners that rely mostly, if not entirely, on bilateral transactions between market participants. Generators selling into these systems usually are required to submit fixed hourly schedules that are set in advance.[31] This arrangement can result in discrimination between vertically integrated utilities who own the transmission network and independent generators who own VERs.[32] Implementing shorter gate-closure periods or shorter scheduling periods in these regions would help mitigate such a concern and reduce the overall cost of maintaining real-time balance between generation and load in systems with high penetrations of VERs. With these points in mind, in a November 2010 Notice of Proposed Rulemaking, FERC proposed to reduce scheduling intervals nationally from 1 hour to 15 minutes.[33] As of October 2011, a final rule has not been issued.

Cooperate among Balancing Areas

Enlarging the regional scope of power system operations through cooperation or integration among balancing areas can offer reliability

By aggregating a geographically diverse collection of VERs, rapid changes in the outputs of individual VERs are replaced by the slower output variations of the aggregated resource.

and economic benefits when integrating large amounts of VERs.[34] By aggregating a geographically diverse collection of VERs, rapid changes in the outputs of individual VERs are replaced by the slower output variations of the aggregated resource.[35] The cause is the geographical diversity in the weather that is seen by geographically dispersed turbines and plants. Figure 3.5 illustrates the impact on variability of spatial dispersion of wind resources, a trend that is similar for solar generation.[36]

The economic benefits of cooperation between regions could be significant: the Western Wind and Solar Integration Study identified cost savings across the WestConnect region of $2 billion from a total annual operating cost of $43 billion if the area operated as five large regions rather than many small zones, assuming that adequate transmission exists.[37]

By the same principle, the forecasted aggregate output of turbines over a wide geographic area is more accurate than the forecasts for single turbines. One study found the day-ahead forecast error could be reduced by as much as a factor of two when the geographic region diameter was increased from 140 kilometers to 730 kilometers.[38] Capturing the benefit of wide-area aggregation requires that sufficient transmission be available, which, given the remoteness of many wind- and solar-rich locations, is unlikely without new construction. This issue and recommendations for addressing it are discussed in Chapter 4.

The benefits of geographical smoothing historically have been observed with the aggregation of loads over wide regions. The resulting decrease in variability, balancing responsibilities, and associated increase in market liquidities made cooperation among balancing areas economically worthwhile in many parts of the U.S., decades before VERs became widespread. Utilities in Arkansas, Louisiana, Mississippi, Oklahoma, Nebraska, Kansas, Texas, and New Mexico cooperate via the Southwest Power Pool. Regions like the Midwest, New York, and New England ISOs and the PJM interconnection all grew out of the consolidation of independent balancing areas within their respective regions.

However, cooperation among balancing areas for the explicit purpose of VER integration remains a relatively new activity. A variety of possible cooperation schemes have been proposed, including the interregional communication of regional imbalances, the creation of wide-area balancing markets, the provision of operating reserves from other jurisdictions, the transfer of load responsibilities from one jurisdiction to another, and interhourly or dynamic scheduling between balancing areas. The North American Electric Reliability Corporation (NERC) has recognized the need to review and study interregional cooperation, and industry-led efforts exist.[39] For example, WestConnect created the Virtual Control Area Work Group to investigate methods and technology available for participating balancing areas to function as a single "virtual" control area for specific operations, and the Bonneville Power Administration has several pilot programs in place.[40] Ultimately, the transmission capacity that exists between neighboring balancing areas will determine the degree to which cooperation or consolidation is possible. Limited transmission between balancing areas may slow their aggregation. However, this issue has not been studied in depth in the U.S.

FINDING

Improving forecasts, reducing gate-closure and operating periods, and expanding cooperation among neighboring balancing areas are operational changes that can offer reliability and economic benefits when integrating growing variable energy resource penetrations. System operators and utilities in many regions in the U.S. are making progress toward implementing these changes.

3.3 ENSURING ADEQUATE SYSTEM FLEXIBILITY

The operation of a system with a substantial presence of VERs will be different from today's operation. The future well-adapted mix of generation technologies also will change, probably reducing the proportion of less flexible baseload units and increasing the percentage of more flexible resources, always depending on the level of VER penetration. These flexible resources must be capable of continuously modifying their output, or "cycling," to accommodate the variation in the output of the VERs.

Flexibility is not a new concept in power systems; however, its importance has been greatly amplified in recent years by the prospect of large penetrations of wind generation.[41] Power system flexibility has both technical and economic components. Technically, the rate at which a generator can change its output, known as its ramp rate, is limited by its design and technology. Some units, such as nuclear and large coal-fired generators, have slow ramp rates; substantial changes in output can take hours to tens of hours. Other units, such as gas turbines, can effect changes in their output within fractions of an hour, while hydro units can ramp in fractions of a minute. But requiring resources to cycle frequently has negative economic consequences. Large baseload units and midrange plants that were not designed for frequent cycling will incur increased maintenance costs, reduced life, or both; their varying output moves generators away from their point of maximum efficiency; and the financial compensation paid to generators for their start-up costs may become significant. These plants, characterized by relatively high capital costs but low variable costs, need to operate with high capacity factors in order to remain economically viable, further increasing the financial incentives they would need to cycle regularly.

The increased demand for flexibility from VERs will not necessarily translate into a need for new capital investments. In Europe, several regions already experiencing high penetrations of wind power have had enough flexibility in their existing generation fleets to successfully integrate significant levels of wind without substantial new dispatchable generation investment.[42] In preliminary studies of VER integration in North America, some regions have concluded that they, too, already have sufficient flexible capacity to accommodate the anticipated growth in VERs over the next decade or two.[43]

FINDING

The existing generation fleets in some regions appear to have sufficient flexibility to accommodate levels of variable energy resource penetration anticipated during the next decade, although this is not universally the case.

As expected VER penetrations continue to increase, however, regions with organized wholesale markets may have insufficient investment in flexible plants due to the uncertainty regarding the most appropriate technology mix, the rate of renewables growth, and the economics of such a mix under anticipated future prices and operating conditions. Several European countries with significant or anticipated penetrations of wind generation are currently addressing this issue.[44] There is no consensus yet on the most appropriate solutions, which could include enhanced capacity mechanisms, new categories of remunerated ancillary services, or other regulatory instruments. If necessary, appropriate regulatory measures or changes to market design should be developed to facilitate adequate levels of investment in flexible generation plants to ensure system reliability and efficiency.

Another important issue is offering sufficient incentives to ensure that flexible resources will offer their flexibility to the power system. A recent study by the International Energy Agency found that more than the incentive provided by fluctuating electricity prices will be needed to prompt owners of flexible resources, particularly of slower, intermediate, or baseload plants, to offer the full extent of their flexibility to the markets. The agency plans to address this topic in the next stage of its Grid Integration of Variable Renewables project.[45]

FINDING

Generators require strong and clear economic incentives to make investments in flexibility and operate flexibly within the system. Research is needed to design market rules and incentive mechanisms for this purpose.

In this section, we describe several existing and upcoming resources capable of offering flexibility to systems with high VER penetrations. In practice, their usefulness may be limited if transmission constraints exist. With key transmission lines congested, the most economic flexible resources can become inaccessible, requiring the dispatch of more expensive resources.

Thermal Generation

Thermal generators—mainly coal, gas, and nuclear—account for around 90% of the capacity of the U.S. generation fleet.[46] They supply the bulk of the flexibility within the power system today by participating in energy markets and offering dispatchable capacities, such as operating reserves. Peaking plants, including diesel and gas combustion turbines, can be quickly started and ramped. However, they can be costly to operate because of higher fuel costs and lower efficiencies. Intermediate plants, including combined-cycle gas turbines, improve on the efficiency of peaking plants, losing some flexibility in the process. Baseload plants, including nuclear, coal, and some combined-cycle gas generation, are not usually operated flexibly. While they have the lowest per-kWh operating cost, they generally have relatively narrow power output ranges and slow ramp rates, and they incur significant real and opportunity costs when made to ramp and cycle.[iv] The optimal mix of the three categories of generation should consist of a portfolio with an adequate balance of flexibility and production costs.

While some technological limits exist in the flexibility available from thermal generation, experience has shown that the factors constraining their flexibility are mostly economic. Making a thermal generator flexible and accessing this flexibility incurs costs. Designing a flexible thermal plant and operating it flexibly require

[iv] It is technically possible to operate nuclear generation facilities flexibly. Achieving flexible operations requires relatively minor technical modifications to plant designs and fuel content. Électricité de France regularly cycles their reactors to provide a range of grid services, including primary frequency regulation and daily load following. Some of their units experience up to 250 power variations between 10% and 80% of their nominal rated capacity per year.[47]

Constrained by the need to comply with emissions regulations, some thermal generators may require additional emissions-reduction investments before their flexibility can be accessed.

a number of redesigns and operating practices that all decrease the efficiency of the system. Furthermore, continuously cycling thermal generators will increase maintenance costs and decrease equipment reliability and life. By reducing efficiency, cycling fossil fuel–based generation also may increase emissions of carbon dioxide, nitrogen oxides, sulfur oxides, or particulates, especially in the case of coal generation.[48] Constrained by the need to comply with emissions regulations, some thermal generators may require additional emissions-reduction investments before their flexibility can be accessed.

Hydro Generation

The success of wind in Denmark and its integration in the Nordic countries is generally attributed to the availability of good interconnections and large quantities of hydro generation in this region, particularly in Norway.[49] Hydro generation has two characteristics that make it a highly flexible resource.[v] First, these facilities are able to rapidly ramp their output over a wide range while maintaining high efficiency. Second, they can store potential energy for later generation by varying the water levels of their reservoirs.

VERs can offset hydro production when their production levels are high and allow water to accumulate in hydro reservoirs. The water collected then can be used to generate power when VER production levels are low and marginal production costs are high enough. Hydro is also an economical form of generation because it can operate with essentially zero fuel cost, although water used for generation today will not be available if needed in the future, incurring an opportunity cost.

In practice, the operation of hydro generation is usually subject to limits in place to minimize flooding and other adverse impacts, for example on fish migrations, water quality, aquatic ecology, tourism, and nearby residents and businesses. These limits can restrict their flexibility, particularly during times of abnormally high or low water. The high water flows along the Columbia River during the summer of 2010 limited the flexibility of the Bonneville Power Administration’s hydro generation, as the plants were forced to operate in order to minimize water spilling over the dams and keep total nitrogen saturation at levels safe for fish. This loss of flexibility coincided with a period of high wind, forcing wind generation to be involuntarily curtailed.[50]

Concerns over flooding and environmental impacts limit not just operation but the construction of hydropower facilities.[51] As a result, hydro generation in the U.S. makes up only about 8% of total capacity and supplies around 7% of total energy, even though it is highly viable as a generation technology.[52] However, some potential for capacity expansion has been identified from small hydro and the conversion of non-powered dams to powered ones.[53] It is unclear how much grid flexibility would be obtainable from these plants, as many of them may end up being built with limited water storage capacity. The future role of hydro generation for the purpose of providing system flexibility is likely to be valuable but limited.

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[v] In this report, “hydro generation” refers to impoundment, or dam-based, hydropower unless otherwise noted. This is in contrast to run-of-river hydropower installations with little or no water storage. By avoiding the high dams and extensive land inundation that characterize impoundment hydropower, pure run-of-river installations are typically smaller and have less impact on the environment. However, these facilities produce variable outputs and are often categorized as a type of VER.[54]

Additional Sources of Flexibility

Faced with the economic trade-offs surrounding flexible thermal generation and the scarcity of resources for hydro generation, demand response and energy storage could play important roles as new sources of flexibility in the future. Because demand response works by offsetting physical generation, it has the potential to offer flexibility at lower marginal costs and emissions than thermal generation.

Demand response, discussed in detail in Chapter 7, occurs when customers modify their electricity use in response to signals from the system operator or changes in the price of electricity. In the context of VER integration, demand response that is sufficiently nimble and reliable has the potential to offset operation and capital investments of more expensive flexible generation. Where VER output is not well correlated with load patterns, as often is true of on-shore wind, time-varying prices may induce load shifting that makes better use of off-peak VER generation.

The earliest and most widely adopted application of demand response in the context of flexibility is in response to reliability threats. Emergency and interruptible load programs provide customers with incentive payments or rate discounts in exchange for load reductions during declared system emergencies. When unusually high demand or loss of a major generator or transmission link threatens a power system's operating reserve margin, demand response may be used to maintain stability by calling on customers to shed load or manually disconnecting specific customers from the grid. This technique already has been extended to protect system reliability during VER ramp events, including a February 26, 2008, event in the Electric Reliability Council of Texas (ERCOT).[55] As discussed in the Western Wind and Solar Integration Study, this application of demand response reduces costs by avoiding the need to hold additional reserve generation online for all 8,760 hours of the year to deal with relatively rare ramp events.[56] In some regions with wholesale markets—most notably ERCOT—demand response represents a small but growing share of operating reserve and regulation service markets, providing real-time flexibility on a more routine basis.

In the context of VER integration, demand response that is sufficiently nimble and reliable has the potential to offset operation and capital investments of more expensive flexible generation.

A challenge of expanding traditional load-control demand response programs to accommodate VERs is the concern that more frequent activation may lead to fatigue and an eventual lack of willingness of load to participate. This has not been targeted in demand response pilots, and merits further study. Use of demand response for higher-frequency adjustments also requires a better understanding of the speed and predictability of the response of load to control signals and the behavior of end users in an environment of rapid and perhaps frequent curtailment or load adjustment. Dynamic pricing programs that provide customers with greater transparency and control may offer attractive alternatives to load control programs, particularly if combined with automated control technology. As discussed in Chapter 7, dynamic pricing is in its infancy in U.S. electricity markets, although successful long-term programs, such as Georgia Power's real-time pricing tariff for large industrial and commercial customers, suggest its efficacy.

Energy storage using pumped water, compressed air, batteries, flywheels, and other storage technologies could also supply flexibility.[57] Pumped hydro energy storage (PHES), where the generator and water turbine can operate as a motor and pump, is of particular value as a flexible resource. During periods of excess energy from VERs, water can be pumped into the elevated reservoir and used to generate at a time when rapid up-ramping is required, providing time for slower units to respond. The U.S. currently has approximately 22,000 MW of PHES capacity.[58]

PHES facilities do face important limitations. They are only viable in locations that have sufficient water availability and are capable of siting large reservoirs at different heights. Many of the best locations for PHES facilities in the U.S. have already been developed. Environmental concerns regarding the construction of large dams and reservoirs further restrict the viability of additional PHES installations. Only one PHES facility with capacity of more than 100 MW has been constructed in the past 15 years.[59] FERC has recently issued preliminary permits to more than 40 projects that total over 32,000 MW of additional PHES capacity.[60] However, a preliminary permit does not authorize construction, and it is unclear how many of these projects will eventually be constructed.

Compressed air energy storage (CAES) is the only other storage technology that has achieved long-term utility-scale operation. CAES facilities use electricity to compress air and inject it into underground caverns for storage. When the energy is needed, the compressed air is heated and run through a turbine to generate electricity. Only two utility-scale CAES facilities have been constructed worldwide: a 290 MW facility with two hours of storage in Huntorf, Germany, that entered commercial operations in 1978 and a 110 MW facility with 26 hours of storage in McIntosh, Alabama, that entered commercial operations in 1991. Supported in part by funds from the American Recovery and Reinvestment Act of 2009, New York State Electric & Gas and Pacific Gas & Electric have recently announced plans to construct new CAES facilities with respective storage capacities of 150 MW/16 hours and 300 MW/10 hours.[61] These efforts promise to advance the maturity of CAES technology and reduce the uncertainty regarding its cost at commercial scale.

To date, utility-scale battery and flywheel technologies have achieved limited energy capacity and have only been deployed in a small number of pilot projects.[62] These technologies remain too costly for most applications today, at a price about two to five times higher than competing sources of flexibility.[63] Storage technologies are currently the focus of research, and costs could fall in the coming decades. If they do, the use of bulk energy storage in the power system could expand dramatically.

Obviously, curtailment of VER generation is another source of flexibility. VER output can be reduced by temporarily disconnecting individual generators. Some advanced wind turbine designs also allow controlled feathering of their blades to partially reduce their output. While VERs do not appear to provide operating reserves anywhere in the U.S. today, studies have shown they are technically capable of doing so.[64]

In some cases, curtailing VER outputs can be the economically optimal decision—for example, during “minimum generation events” when the combined generation of wind and baseload facilities exceeds the load. If the baseload plants are already operating at their technical minimums, either they must be shut down or the wind plants must be curtailed. This latter option is often more economically efficient in the short run because it avoids the large costs associated with shutting down the baseload plants and then starting them up a short time later. In the long run, the prospect of baseload units being shut down during minimum generation events would provide added incentive for investments in plants that can operate more flexibly at lower cost. Significant penetration of VERs in general will cause baseload generation facilities to cycle more frequently, potentially leading to loss of efficiency of these plants and potential emissions increases, though this issue is not yet well understood.[65] VER “must-take” operating practices, as they are currently established in the EU, will amplify this effect.

FINDING

Care must be taken in the design of operating procedures to ensure that the option to curtail the output of VERs is always available to operators and that it is selected when it is economically efficient to do so.

3.4 INTERCONNECTING VARIABLE ENERGY RESOURCES

Beyond the variability and uncertainty of their outputs, VERs exhibit other characteristics that are very different from conventional generators. Wind turbine generators do not operate at constant speed, which in most cases results in an ac output with variable frequency and voltage that is not directly compatible with the grid. Solar PV systems produce a dc voltage, which also cannot be directly connected to the grid. Both require an interface system based on power electronics that converts their outputs to grid compatible form.

The physical characteristics of VER generation and its specific connection to the grid result in a different contribution to the inertia of the power system than that of conventional plants. All conventional forms of generation produce electricity by rotating a large metal mass within a magnetic field. Conventional generators also include a rotating turbine with large mass. The considerable stored kinetic energy of this aggregate mass gives these machines the transient ability briefly to provide electrical output power in excess of or below their mechanical input power to accommodate a sudden change in load—in effect, to act like a shock absorber for the system. Power systems rely on this inertial response for maintaining system stability. During such a transient, the mechanical input to the generator is changed to return the generator speed to its proper value.

Most wind turbines and all solar PV plants lack significant inertial response. While wind turbines do store mechanical energy as rotating inertia, there is a significant distinction between them and conventional generators. While the mechanical input power to conventional generators can be increased to return the generator to its correct speed, this cannot be done for wind turbines as the mechanical input power is the wind, and this cannot be increased except in the rare case where the wind turbine output has been curtailed.[vi] When wind and PV account for larger portions of the generation fleet, the inertial response of the overall system will decrease, potentially increasing the risk of power system stability problems. Reduced system inertia due to the displacement of conventional generation with wind already has been observed in the Irish and the Hawaiian systems, and researchers have raised a similar concern for the Western Interconnection.[66] It has been shown that wind generators can provide some degree of inertial response through appropriate design and control of their power electronic interface, and solar PV generators can emulate an inertial response if provided with energy storage.[67] However, as shown by experience, current wind turbines have an inertial response performance below that of conventional generators.[68]

> *When wind and PV account for larger portions of the generation fleet, the inertial response of the overall system will decrease, potentially increasing the risk of power system stability problems.*

Other characteristics of VERs also need consideration. Because of their power electronics–based interface to the grid, VERs can inject harmonic voltages or currents into the grid. This may result in a distortion of the sinusoidal voltage waveform experienced by other pieces of equipment connected to the system, potentially disrupting their operation. The varying

[vi] Some modern wind turbines can employ blade-pitch control to affect some control of input.

power output and complex control systems of VERs could cause voltage to oscillate rapidly, or flicker. Finally, because their response to faults is different from that of conventional generators, VERs often require customized protection equipment.[69]

Most of these challenges can be readily addressed by enforcing a set of interconnection standards. The interconnection standard provisions for conventional generators are designed to ensure that generators do not harm the grid and that they will contribute to the stability and reliability of the grid when required. Due to their very low penetrations, so far VERs in the U.S. have been required to meet few standards. As a result, their expected impact on the system has not yet been properly formalized, and they generally have not played an active role in maintaining system stability and reliability.

FINDING

Before the penetrations of VERs in the U.S. increase to those levels foreseeable with renewable portfolio standards, interconnection standards must be revised to include VERs within the power system and allow them to perform functions that can enhance grid behavior. These functions must be compatible with their unique physical and electrical characteristics.

The nation has made some progress over the past decade on the development of interconnection standards. FERC issued Order No. 661-A in December 2005, specifying that wind generators meet three performance requirements before interconnection rights are granted.[70] The first requires that wind generators not disconnect from the system in response to a transient system voltage reduction, a capability known as "low-voltage ride-through." Power systems employ sophisticated protective relaying and control schemes throughout the transmission system to clear faults quickly when they occur. When faults do occur, the system voltage often drops until the fault is cleared. It is important for generators to remain connected during this time as a substantial loss of generation could further reduce voltage and threaten the stability of the system. The order also requires VERs to provide reactive power support, which allows them to contribute to voltage stability, and it requires wind generators to be compliant with the existing supervisory control and data acquisition systems that utilities and system operators use to remotely control and monitor the power system.

FERC has yet to issue a similar order for solar-based generation technologies. If the penetration of solar generators increases to a significant level, performance standards will become important. Solar PV generators in particular share many technical characteristics with wind generators, so it may be appropriate to extend the provisions of Order No. 661-A to them, as the Interconnection Standards Review Initiative of the California ISO recently proposed.[71] Doing so will require the resolution of inconsistencies between Order No. 661-A and existing standards for solar generation interconnection. For example, Order No. 661-A requires wind generation to have low-voltage ride-through capability, while the primary technical standard governing the interconnection of distributed solar generation requires distributed generation to disconnect immediately upon sensing low-voltage conditions.[vii] NERC currently has two task forces designed to reconcile these standards and develop others for distributed solar generation.[72]

[vii] This provision is in the Institute of Electrical and Electronics Engineers Standard 1547.

Recent technical developments have enabled engineers to construct wind generators that are compatible with most of the stability and reliability performance requirements typically imposed upon conventional generation.[73] Manufacturers typically construct modern VER plants with advanced power electronics and controls. Among other capabilities, these power electronics give plants reactive power control. Advances in mechanical engineering also have allowed modern wind turbines to curtail their power outputs with precision and in real time through rotor pitch control. This capability, known as active power control, allows the turbines to maintain a fixed power output below maximum or a maximum up-ramp rate.

NERC, ISOs, RTOs, and utilities are closely monitoring the impact of VERs on grid reliability to determine whether existing requirements should be modified or additional requirements are needed. Following recommendations from its 2009 report on integrating VERs, NERC has created a subgroup within its Integration of Variable Generation Task Force to review the adequacy and consistency of U.S. interconnection standards for all generation, both VERs and conventional.[74] The task force is expected to release a report by the end of 2011 making recommendations on interconnection issues.

FINDING

Interconnection requirements for all generation technologies, both variable energy resource and conventional, must be designed for anticipated rather than existing conditions. The technology necessary to comply with anticipated standards is available.

3.5 CONCLUSIONS AND RECOMMENDATIONS

Motivated by state and federal policies, the proportion of generation from VERs in the U.S. could grow substantially over the next several decades. While variability and uncertainty are familiar concepts in power systems, wind and solar generation, as new sources of both, could complicate power system operations and planning.

High penetrations of wind and solar generation will require operators to procure additional operating reserves. Increased operating reserve requirements are viewed as one of the primary sources of potential system operations cost increases associated with the growth of VERs.

Improving the accuracy of VER power production forecasts and VER ramp event forecasts could reduce the magnitude of these cost increases. Improving both types of forecasts relies critically on forecasting methodological improvements and the increased availability of granular meteorological data, especially data measured at individual VERs.

RECOMMENDATION

Industry and government should work to expand the sharing of granular meteorological data measured at VER sites for the purpose of improving wind power production forecasts.

Changes to system operating practices could also facilitate the cost-effective integration of high penetrations of VERs. Integrating forecasts fully into power system operations could yield significant benefits and remains an important challenge, but one industry appears to be tackling well. Moving the deadline when generation schedules become final and binding closer to real time and reducing the duration of generation commitment periods would allow system operators to take advantage of the fact that wind forecast accuracy improves appreciably closer to real time. These changes promise to reduce the overall cost of maintaining real-time balance between generation and load in systems with high penetrations of VERs.

Merging or expanding cooperation between neighboring balancing areas, as well as reinforcing when needed the interconnection capacity among them, also would reduce the impact of growing VER penetrations on operating reserves.

RECOMMENDATION

Fully integrating wind forecasts into system operations, moving scheduling decisions closer to real time, and expanding cooperation among neighboring balancing areas are all operational changes that should be considered in regions that expect high VER penetrations. These changes can reduce the negative impact of high VER penetrations on system operating reserve requirements.

High penetrations of VERs will amplify the importance of power system flexibility. Flexible resources will be needed to accommodate the variation in the output of VERs. Many regions already have sufficient flexibility in their existing generation fleets to accommodate the VER penetrations anticipated in the immediate future. However, additional flexibility may be needed in other regions and further into the future. This flexibility can be provided by thermal or hydro generation, demand response, and energy storage. But it is likely to prove difficult to expand hydro capacity. There are concerns regarding the ability of present wholesale market designs to attract the necessary volume of flexible resources.

RECOMMENDATION

As VER penetrations increase, mechanisms that provide incentives for investment in flexible generation and for operating flexibly should be devised and deployed. The design of these mechanisms is an important area for research today.

Finally, beyond the variability and uncertainty of their outputs, VERs also exhibit other physical and electrical characteristics that are very different from conventional generators. As anticipated VER penetrations increase, it will become increasingly important to design VER grid interconnection standards that allow VERs to enhance grid functionality while remaining compatible with their unique characteristics. The U.S. has made considerable progress in this area in recent years, and a variety of organizations are continuing to closely monitoring the adequacy of existing interconnection requirements.

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