Chapter 3
Renewable Generation, Integration of

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Glossary

Ancillary services	All of the actions necessary for supporting the transmission of power from the generator to the consumer and ensuring reliable system operations. Some examples of these services include: voltage and frequency control, generation scheduling, load following, and system protection.
Balancing area	An area in which electricity supply and demand are locally matched and over which a balancing authority maintains system frequency and provides operating reserve.
Independent system operator	The organization that is charged with controlling the operation of the electrical power transmission system in a certain geographic area.
Operating reserve	Extra generating capacity available at short notice to replace scheduled capacity that is currently unavailable due to some sort of system disruption.
Unit commitment and economic dispatch	The process by which generators are scheduled by the grid operator in order to meet expected demand at all timeframes. Commitment refers to deciding which

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	generators will be turned on far in advance of the time period under consideration. Dispatch refers to the decision of how much power each generator will supply during a timeframe that is closer to realization than the commitment period.
Variable generation	Generation from units that cannot be well controlled and thus are not perfectly dispatchable. This term is often applied to generation from weather-driven units, such as wind and solar.

Definition of the Subject and Its Importance

The integration of renewable generation consists of all of the changes in power system operations that are required in order to allow renewable generation sources to play a significant role in the electricity system. The impacts are mostly due to variable generation (VG), like wind and solar power. Historically these technologies have been labeled as intermittent generation, but recent trends prefer the label variable generation [1]. Variable generators have a maximum available generation limit that changes with time (variability) and this limit is not known with perfect accuracy (uncertainty). This uncertainty and variability is in addition to that of the existing system and can therefore create additional challenges for grid operators to maintain their current levels of reliability.

Introduction

Renewable electricity generation encompasses a number of distinct technology types, often classified by their power source, such as geothermal, hydroelectric, marine, biomass, solar, and wind power. Within each of these groupings there are a number of different technologies for harnessing the energy of the power source. However, when discussing renewable integration wind, marine, run of river hydro, and solar generation tend to garner most of the interest. This is due to the fact that the output of these plants is variable and uncertain. Other types of renewable generation are more similar to traditional power sources, such as fossil fuels and nuclear power, in that they are dispatchable. This means that they can be reliably scheduled in advance to provide power when desired, and do not need to rely on the current weather conditions. This is the result of the fact that the availability of their energy source can be controlled. While no generator can guarantee availability at a scheduled time, every generator has the possibility of being unavailable. The unplanned outage rates for dispatchable generators are low enough for the system to treat them as if they will produce at the desired level in the scheduled timeframe, while holding contingency reserves should an outage occur. While other renewable generating units can occasionally have uncertain output, for example, hydroelectric units cannot operate below certain reservoir levels, they are normally treated similarly to conventional units. For this reason the integration of these generating technologies is not normally considered an issue for electrical system operation. Another way of demonstrating the difference between variable generation and dispatchable generation is to examine some of the factors used to describe their patterns of usage. One common metrics is the capacity factor. A capacity factor is the amount of electricity a unit would be physically able to generate divided by the theoretical maximum that the unit would produce if it ran at full capacity over a certain time period. Therefore times when the unit would be down or at a reduced capacity due to forced and unforced outages count against the capacity factor. Baseload power plants typically have capacity factors on the order of 90% or higher. Wind power plants sited in good onshore locations have capacity factors of around 30%, while solar PV plants, even in very good locations, tend to have capacity factors under 20%. However, capacity factor alone does not tell the whole story. For example, a natural gas turbine that is used only for peaking may have a capacity factor under 5%. Even though the turbine is available for a greater percentage of the time, it is not always chosen in the unit commitment and dispatch process due its higher operating costs than baseload plants. For this reason other metrics such as forced and unforced outage rates are also used to characterize unit usage. These metrics however do not apply as well to variable generators and therefore metrics such as capacity value and effective load-carrying capability are often utilized when discussing the availability of wind and solar generators. When the integration of renewable generation is considered, wind and solar generation are usually the focus due to their variable and uncertain nature and their current presence in relatively large quantities in the system.

Worldwide wind power output grew sevenfold and solar photovoltaic (PV) production grew 16-fold from 2000 to 2008 [2]. Wind power has been the fastest growing source of electrical generation capacity in the United States for the last several years [3]. In 2009, there were over 34 GW of wind capacity operating in the United States and over 600 MW of solar PV [3]. These trends have transformed variable generation from a minor component in the electricity system to a contributor whose effects on the overall system must be thoroughly considered. As the future electricity system is expected to contain even larger quantities of variable generation, it is important that means of integrating variable generation are well researched before the higher penetration rates are achieved.

Electricity System Background

The current electricity system is the product of over 100 years of evolution and growth. A central pillar of the system is dispatchable generation, generally from fossil fuels, hydroelectricity, and nuclear power. As most large-scale power systems

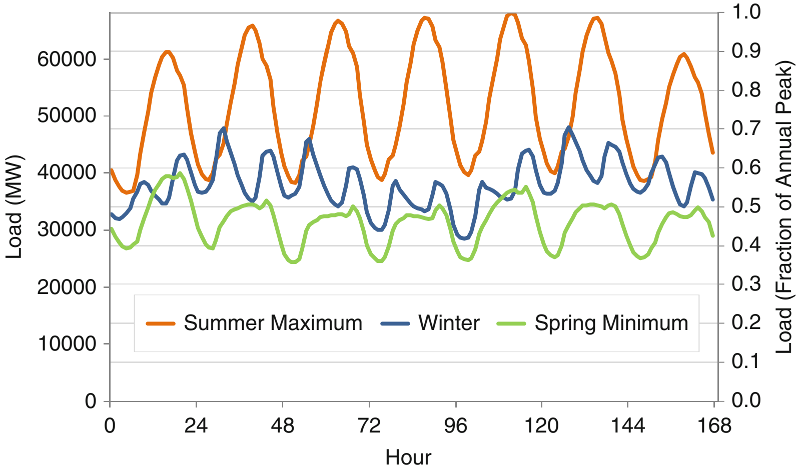

Fig. 3.1 Hourly loads from ERCOT 2005 [4]

have relatively small amounts of electricity storage, electrical supply must always meet electrical demand. The instantaneous matching of supply and demand is needed in order to maintain a nominal electrical frequency. When supply does not equal demand, the frequency can change from its scheduled value (60 Hz in the North America, 50 Hz in many other locations). Frequency that deviates too far from its scheduled value can trigger under-frequency load shedding or over-frequency relays disconnecting machines to prevent damage. If this is not controlled, cascading events can lead to blackouts. This need for supply–demand balance coupled with the fact that the vast majority of demand is noncontrollable necessitates the current structure of system operation. Electricity system operation is a complex process where demand must be forecast and generation scheduled in advance, but numerous types of reserves must also be kept waiting in order to ensure system reliability, should forecast demand errors occur or scheduled generation units become unavailable.

Electricity demand follows strong seasonal and daily patterns. Seasonal demand patterns are highly correlated with seasonal weather patterns. Most systems in the United States tend to have their highest demand during the summer due to the large additional loads attributable to air conditioning. European systems generally tend to reach peak levels during the winter due to the demand from electric space heating. Figure 3.1 demonstrates both the seasonal and daily patterns that occur in the Electric Reliability Council of Texas (ERCOT) system. As may be observed, the summer peaks can be as much as double the spring minimum loads. The daily differences can also be very large during the summer months. Figure 3.1 shows an instance where total system load varies between 40 and 60 GW in the course of a single day. In order to meet these vastly different conditions, utilities build generating units with very different production characteristics.

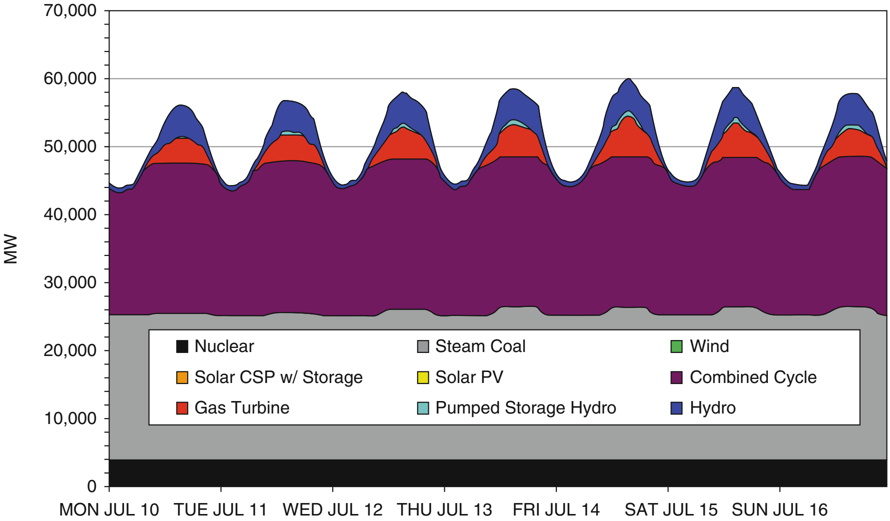

Fig. 3.2 Normal unit commitment and dispatch patterns in the western United States with a very low renewable generation penetration rate [5]

Baseload power plants are utilized to cover the large amounts of demand for electricity that fall below the minimum daily demand level. Coal-fired and nuclear plants are the two most typical types of baseload plants. They are often very high capacity plants that have very large capital costs, and relatively low operating costs. Baseload plants also typically require long start-up times and cannot ramp rapidly to follow changes in load. For these reasons utilities prefer to run the plants as close to maximum output as possible the majority of the time they are in service. Variations in load are usually met through the use of another type of generating unit, the load following plant. These units can be further subdivided into intermediate load plants and peaking plants. Intermediate plants are typically used to meet the daily variability in demand and are often hydroelectric or combined cycle plants fueled by natural gas. Peaking plants usually have a very high marginal cost of production, and as such are only utilized during periods of extremely high demand, often less than a few hundred hours per year. These plants are often natural gas or oil-fired simple cycle turbines. The normal usage patterns of baseload, intermediate, and peaking units can be observed in Fig. 3.2.

The generating units that will meet the expected load are usually scheduled 1 day beforehand in what is known as a security-constrained unit commitment. This optimization of total system costs schedules the start-up of units based on forecasted loads for the next day. Because system load cannot be perfectly forecast, there is the need for another assignment process closer to the actual time point. This process is known as security-constrained economic dispatch and it changes the level of output of units already online in order to ensure that supply meets demand. The amount of time ahead that this process occurs varies by system operator.

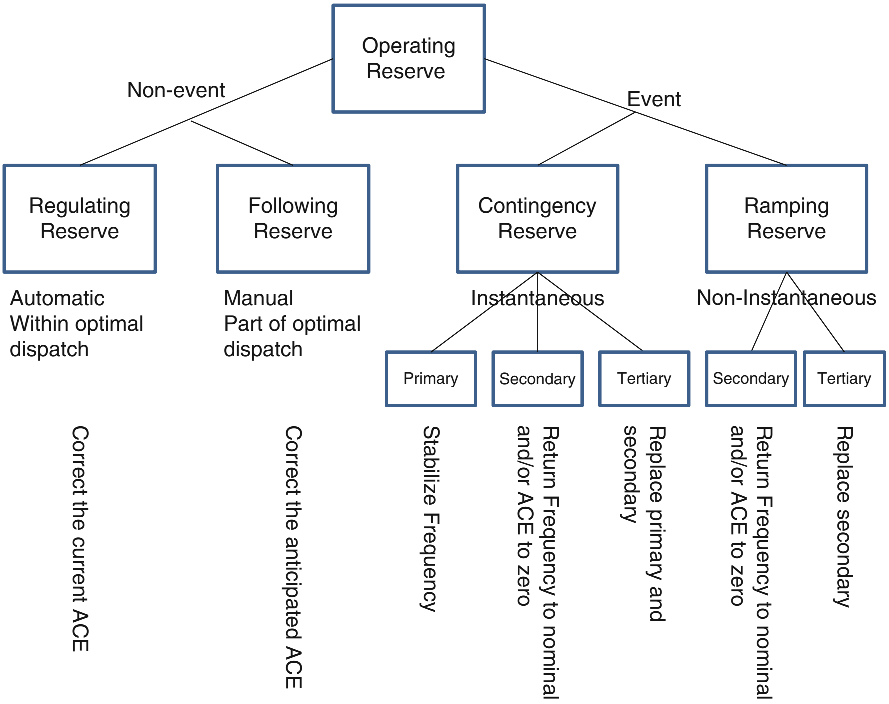

Fig. 3.3 Illustration of reserve types [6]

Advances in telecommunications have allowed some systems to operate at smaller dispatch timings, down to 5 min ahead. Both of these processes should ensure that the commitment and dispatch are secure considering the generator constraints, transmission network constraints, and n-1 contingency constraints. The n-1 criterion states that a system must be secure following any credible single outage, be that a generator, or other system component (e.g., a transmission line).

In addition to advanced scheduling that needs to occur to balance the generation, system operators often schedule capacity as operating reserve to be used in case of unexpected changes from schedules or for variability occurring within a scheduling interval. Operating reserves can be classified according to the type of situation that triggers their deployment, the timescale of the response, and the direction of deployment. Figure 3.3 illustrates the different types of reserves based upon the event type and the speed of response. The most commonly utilized reserves are those that are required during normal operating conditions. Generating units must be kept in reserve in order to respond to continuous differences between forecasted and actual conditions. This function falls under the category of reserves known as regulation reserve. It is employed to respond to the minor random fluctuations that occur around normal load in order to maintain system frequency. Regulation reserves are required in both the up and down directions, in other words, regulation reserve must be able to both increase and decrease output to match the fluctuating conditions. Regulation reserves are generally employed on the sub-minute timescale. More sustained trends over the timescale of minutes are handled through following reserve (often called load following reserve in practice).

In addition, reserves must be kept on hand should a generating plant or transmission line currently importing power suddenly become unavailable. Contingency reserves are those in place for unexpected events that change the instantaneous availability of generators or transmission. Primary reserve, that is, frequency responsive reserves, responds within seconds in order to stabilize the system frequency after a major disturbance. Secondary reserve is then used to restore the frequency back to its scheduled setting. Tertiary reserve is then used to replace the reserve used during the event so that the system is secure toward a subsequent event. Ramping reserve is utilized in order to respond to events that occur over a longer duration, such as variable generation forecast errors or ramping events. Ramping reserve also requires frequency or control error to return to its nominal setting and for it to be replaced in case of a secondary event. However, due to the slow time it takes for these events to occur it is usually not necessary to stabilize the quickly changing frequency. Reserves are also often classified according to their synchronization status. Reserves provided by units that are already running and synchronized to the system are known as spinning reserves, while non-spinning reserves are not synchronized and thus take longer to respond. Fast response reserve, such as regulating reserve and primary or frequency response reserve, require spinning reserve exclusively while slower reserve categories usually contain mixtures of both spinning and non-spinning reserves in different proportions.

Characteristics of Renewable Resources

As described in the Introduction, the discussion of renewable resource characteristics is generally limited to wind and solar generation, since they operate quite differently from other types of generation. While both are considered variable resources, wind and solar generation have distinct characteristics that need to be considered when attempting to integrate them into the electricity system. Perhaps the most important difference is in their diurnal patterns. Solar generation output follows the daily cycle of the sun in its particular location on earth, and thus is limited to daylight hours. Wind power output may occur during both daylight and night hours, but in most locations output has a tendency to be higher and more consistent during the night hours. This is demonstrated in the plot of average wind power output over the course of a day for the year 2004 in the MISO system seen in Fig. 3.4. Plotted on the same graph are the average locational marginal prices (LMPs) for the MISO system over the course of a day. As may be observed, the wind output tends to be highest when energy prices are lowest, corresponding to times of low demand, and dips during the daily peak when prices are highest.

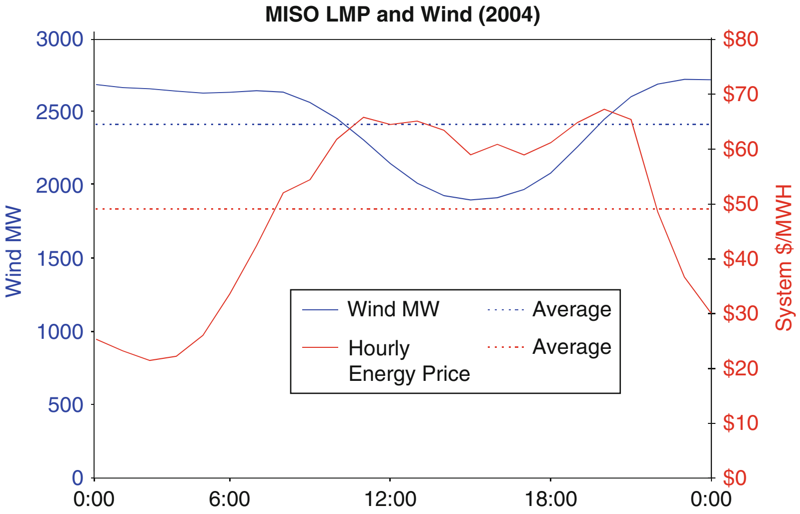

Fig. 3.4 Average energy prices and wind power output over the course of the day in the MISO system [7]

Solar generation can be subdivided into two different categories: concentrating solar thermal and solar PV. From an operational perspective the biggest difference between the two is that concentrating solar thermal plants can have thermal storage capabilities. This allows them to store energy that can later be used to provide electricity during periods where output would be diminished if relying solely on immediate solar irradiation. Solar PV on the other hand is completely reliant on the immediate solar irradiation and thus has reduced output in cloudy weather, and no output at night. The difference in daily profiles for concentrating solar thermal plants with storage versus PV plants can be seen in the July portion of Fig. 3.5. Another major difference between the two technologies is the locations in which they can be deployed. Concentrating solar thermal plants require larger areas for installation and the high capital costs dictate that they be deployed in only very high quality resource areas with high direct normal irradiance. Solar energy contains both a direct and a diffuse component. The direct component is the light from the solar beam and the diffuse component consists of light that has been scattered by the atmosphere. The direct component can be focused using mirrors or lenses and accounts for 60–80% of total solar insolation in clear sky conditions, but decreases with high levels of humidity, cloud cover, and atmospheric aerosols. This limits their construction to arid regions, such as those in the southwestern United States. PV on the other hand can be deployed in nonutility scale system sizes and thus can be present in large plant configurations or distributed over a number of locations, such as rooftops. This can be an important distinction in the case of very high levels of distributed PV penetration as the output from these locations only appears to the system operator as reduced load.

Wind generation is also subdivided into two categories, though usually based on the location of the wind plant, not the technology being used. Onshore locations

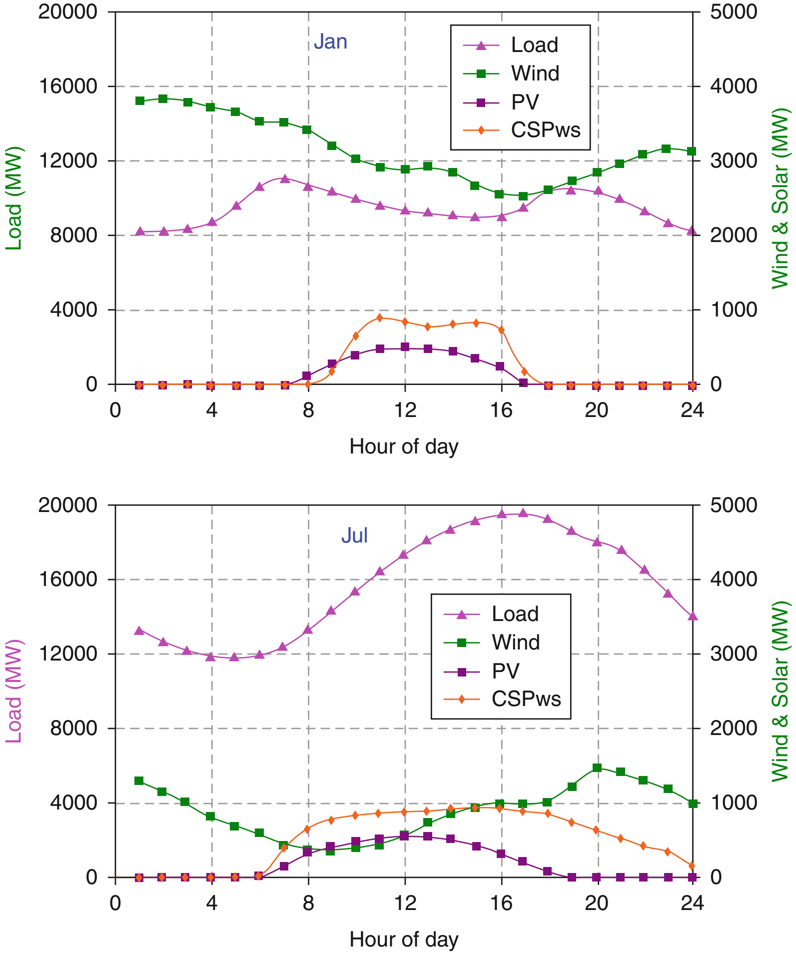

Fig. 3.5 Load, wind, solar pv, and concentrating solar thermal (with storage) daily profiles for both January and July in Arizona in a high renewable penetration scenario [5]

have been the dominant choice thus far as wind power capacity has grown. However, offshore locations generally have more consistent output and the accompanying higher capacity factors are attractive. Offshore locations tend to involve the construction of larger turbines, and are usually more expensive due to the difficulties associated with their construction in large bodies of water. While onshore locations can require building new transmission, the additional transmission demands of offshore locations are more extensive, but conversely have the advantage that they are generally located closer to load centers.

One very important positive aspect of both wind and solar is the large size of the resource base. For example, while global electricity consumption in 2005 was estimated to be 16.6 PWh, the resource base of global onshore wind power, restricted to locations with a minimum 20% turbine capacity factor, is approximately 700 PWh [8]. The global offshore resource base, while not as large, is still considerable. Even after restricting the locations to those within 50 nautical miles of the coast and water depth of 50 m or less, the potential energy production is still approximately 80 PWh [8]. The total potential capacity of offshore wind power in the United States is over 4,000 GW, based on locations within 50 nautical miles of the coast with average annual wind speeds at 90 m greater than 7 m/s [9]. Solar PV power has an even larger potential resource base, with the technical potential estimated to be approximately 4,100 PWh per year by 2050 [10], while concentrating solar thermal potential is estimated to be between 630 and 4,700 GW of capacity [11]. As a point of comparison, small and micro hydroelectric plants have an estimated global technical potential of 150–200 GW of capacity [11]. These enormous resource bases, combined with the current low utilization of the potential energy from these sources, make renewable resources attractive options for long-term planning of energy supply sources.

Because these variable generation sources are not dispatchable, they present new issues for integration into the electricity grid. One major difference is that they are often considered to be a negative load, instead of a generation source. Essentially, any variable generation that is being produced at the current time is accepted and reduces the total load that must be met by conventional generators. This residual load is equal to normal demand minus electricity from renewable generators, and has greater variability than load alone. While this is a suitable representation for low levels of variable generation penetration, it will need to change in order to accommodate higher levels. In fact this is already starting to change as wind is being used to alleviate transmission constraints.

Generator Modeling and Interconnection

There are many technical aspects that concern the physical connection of renewable plants to the electricity grid, and their contributions to stable system operation. As renewable power becomes a larger contributor to the electricity system, it must also take on the responsibilities of maintaining system security. We focus mostly on wind in this section due to the currently higher market share. The requirements of wind turbines connected to the electricity system are prescribed through grid codes that detail the turbine contributions to ensure power system stability. The interactions that occur between the grid and the wind plant are heavily influenced by the type of machine in use and the stiffness of the grid. There are four different types of wind turbine machines commonly in use (Types 1–4), differing in their ability to control output power and reactive power and the type of generator utilized. The creation of accurate models of the physical representation of these different turbines can aid in the understanding of the effects that wind plant interconnection will have on the system. Small wind plants may be connected at low or medium voltage distribution networks. In a larger plant many turbines are connected together through a collector system and then connect to the substation where a transformer steps up the voltage from the distribution level to the transmission level.

Fault Ride Through

One common requirement made of wind turbines is fault ride through in the case of a system fault. Early wind plants would simply disconnect from the system when a system fault occurred. In systems with larger amounts of wind power this disconnection would exacerbate the problem [12]. This requirement specifies that the generator must stay online during faults with a duration and voltage variation under certain thresholds that vary by system. Further advances in wind turbine technology will allow for the post-fault recovery characteristics of turbines to be better than those of conventional generators. While wind turbines must comply with the requirements for normal network operation, they must also have system protection that prevents damage to the turbine during events that take the system out of its normal operating ranges. Plants typically are required to have protection from over- and under-frequency, current and voltage events. Additionally, the type of power electronics utilized by any renewable generation can significantly enhance its response to events.

Frequency Control

Frequency fluctuations in the power system result from an instantaneous difference between the amount of power being generated and the demand, including system losses. Wind plants can contribute to the stabilization of frequency in over-frequency events by decreasing output, either through blade feathering or shutting down individual turbines. Under-frequency events are more challenging because they require additional generating capacity. Since the wind speed cannot be increased to produce more generation when desired, this requires holding a portion of possibly generating capacity free, despite the lost revenue incurred. If decreases in the wind power output can be forecast, the turbines can reduce their output slowly in advance reducing the impact of the negative ramp rate.

Voltage Control

In order for a power system to operate as designed, the voltage throughout the system should be kept within the normal operating range (0.95–1.05 of the set point), though transients are allowed a wider range (0.9–1.1). The impedance of a power line causes a change in voltage between the two ends when a current is flowing. The introduction of renewable generators changes the power flow in the system, and hence the local voltages. Unlike frequency, voltage is a local phenomenon that cannot be controlled system-wide. Thus voltage must be kept within its specified range locally by generators in the area, or by power electronics, such as tap-changing transformers. Voltage control in transmission lines is normally adjusted through the consumption or supply of reactive power by generators, or through capacitor banks or flexible AC transmission system (FACTS) devices.

Reactive Power

Wind turbines with induction generators consume reactive power, which can lead to voltage collapse, if not properly compensated, and increased system losses from voltage drops and reactive current, respectively. To mitigate the effects, reactive power can be supplied through the inverter on variable speed turbines, or through capacitors in fixed speed turbines.

Interconnection Queue Process

The process by which a new generator receives the requisite permissions from the local grid operator to connect into the transmission system is known as the interconnection queue process. This process enables the system operator to conduct feasibility, system impact, and facility studies to ensure that the new generator will not have negative effects on system operation. The process also includes the planning steps necessary for generator participation in local markets and the acquisition of necessary transmission rights.

Operating Impacts

With the increasing amounts of wind power being added into electricity systems in recent years, a number of studies have been conducted in order to assess the impacts on the system incurred by integrating these large amounts of wind power. These studies typically examine two cases, one with wind and one without, and compare the results of statistical and production cost simulation analysis in order to determine the cost differences in system operation that may be attributed to wind power. A common assumption is that system reliability must be held at a constant level, which may necessitate the inclusion of additional operating reserves in the with wind case to remedy the increased system variability and uncertainty introduced by the wind plants.

Regulation

The goal of regulation is to compensate for the system variability at small timescales. The majority of this variability is due to normal load fluctuations, with an additional component of variability attributable to conventional generators minor deviations from their set points. The addition of renewable generation to the system adds another source of variability that must be accounted for. However, the impacts of wind generation on regulation services have been found to be relatively minor. For example, the addition of 3300 MW of wind into a system with approximately 30 GW of system peak load required only 36 MW of additional regulation [13]. This is due to the fact that the variability of a large number of wind turbines aggregated together is fairly small at the regulation timescale. Additionally, load and wind power are uncorrelated on the small timescales considered for regulation and thus their fluctuations are rarely amplified and often cancel each other out. However, studies are continuing to use different methods to determine the impact to regulation reserve, and the requirements differ sometimes substantially.

Load Following

One of the areas where the integration of renewable generation sources can have a major impact on grid operations is in the load following domain. In the minutes to hours time frame in which load following operates, there can be large ramps in renewable generation output. The addition of variable generation to load increases the overall system variability within this timeframe. For example, these effects occur when wind power output starts to ramp down following its diurnal pattern, just as the morning load starts to ramp up. This case marks extremely poor timing for the system operator as they must not only be able to handle the increase in load, but must simultaneously replace power that was being generated.

Wind Uncertainty Costs

The main costs of wind uncertainty are the result of having a suboptimal generation mix online due to an inaccurate forecast. One example of a commitment cost can be seen in the case of wind over-forecasting. If the wind output is forecast to be high, but is actually much lower in real time, a unit must be ready to serve the load that the wind was scheduled to serve. If this amount is significant it is possible that a slow starting baseload unit should have been made available at this time. In this case the wind overestimation causes an expensive fast starting unit to produce when a cheaper, but slow starting, unit would have been chosen if the forecast was more

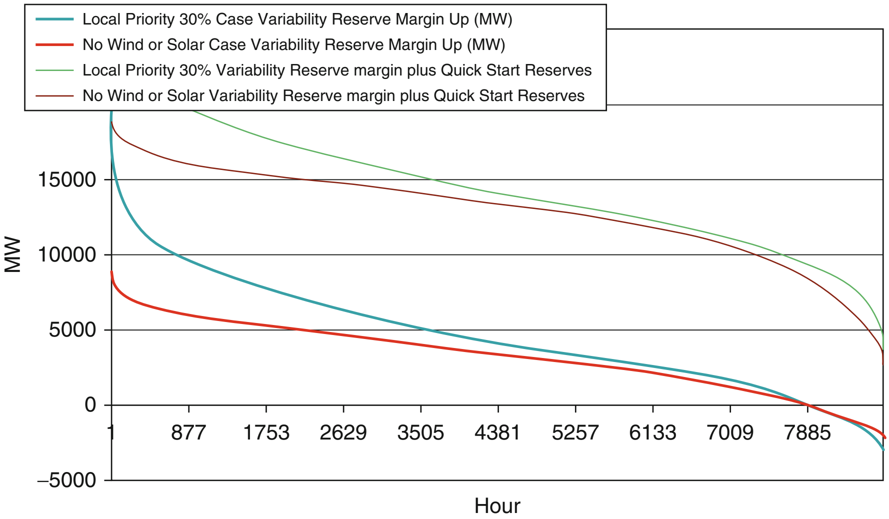

Fig. 3.6 Increase in available spinning reserves for a base case and a high renewable penetration rate case [5]

accurate. On the other hand, if the wind is under-forecast there may be more plants online than is necessary, causing higher start-up and fuel costs and leading to the possibility of wind curtailment.

It is important to note that since individual wind and solar plants are currently always smaller than the largest generator in the system, additional contingency reserves are not required by traditional metrics, such as the n-1 criteria. This could change in the future at higher renewable penetration rates if very large renewable generation plants are installed, or in the case of number plants being routed through a single large transmission line. However, at very high renewable penetration rates it can be expected that very large renewable forecast errors could lead to situations where even contingency reserves are not sufficient to cover the error, as has been seen in a study of the western United States [5]. In the Western Wind and Solar Integration Study (WWSIS) it was found that these errors occur in approximately 1% of operating hours. While additional spinning reserves could be added to the system to handle these extreme events, it was proposed that some form of demand response would be more economic. While additional reserves of up to one to one backup have been proposed, this ignores the fact that the addition of renewable generation increases the amount of up-reserves available in the system. The incorporation of increased renewable sources causes the backing down of traditional generators, creating larger amounts of spinning reserve available to the system, as was shown in the WWSIS. One example of this result is shown in the up-reserve duration curve in Fig. 3.6. The amount of down spinning reserve is also increased as wind curtailment provides a very simple option.

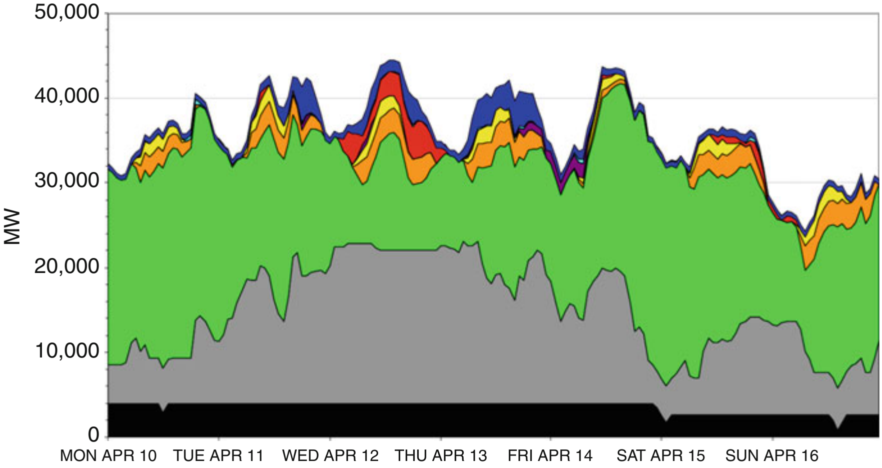

Fig. 3.7 An example of unit commitment and dispatch in the western United States with 30% renewable generation penetration [5]

Thermal Unit Cycling

At very high penetrations of renewable generation it is not only peaking and intermediate units that are displaced.

Figure 3.7 shows an instance where baseload power is forced to produce at levels below maximum generation because of the large amounts of renewable power provided in a 30% renewable penetration scenario. When baseload generation must frequently change its level of output it is referred to as cycling, and it imposes additional wear and tear costs on units that were designed for near constant output. This particular instance is a case where a combination of low demand and high wind output combine to produce results that are far from normal system operation. The most damaging cycling events for thermal units are those where large changes in temperature cause material fatigue, decreasing the normal life of generator components. For this reason unit start-ups are the most damaging due to the large temperature differences between the operating mode and the shutdown mode. The length of the shutdown period is also important with hot-starts and warm-starts being preferred to cold-starts. Though less damaging than shutting down, bringing the generator down to its minimum output level, and then back up to maximum output, also creates large temperature changes that increase wear and tear on the unit.

Market Considerations

While it has been shown that low levels of renewable generation can be incorporated into the electricity system, with few or no changes to current system operations, the variable and uncertain nature of wind and solar power do create limitations on the penetration rates that are reasonably achievable within the context of the existing system. The effects of the uncertainty and variability are mitigated by large day-ahead and hour-ahead markets that provide many options for the balancing of supply and demand.

Balancing Area Cooperation

In 2010, there were over 100 balancing areas in the United States and Canada. Recent trends favor balancing area consolidation and the number of balancing areas is expected to continue to decrease. This is a positive development for the integration of renewable generation. Small balancing areas suffer larger consequences from routine variability. This is true for both supply and demand. For example, in a system with 100 MW total demand, an increase in demand of 10 MW is very significant, while in a system of 10,000 MW the 10 MW change is much more easily accommodated. Aggregated demand is also less variable for larger systems due to the larger number of individuals, and hence the smaller roles of the individuals in the aggregated system load. The variability of renewable generation also decreases with the aggregation of multiple generators in different locations. This geographical diversity of variable generation is due to the fact that the further the two generators are apart, the less likely they are to be affected by the same weather patterns, and hence the correlation of their power output is lower.

Figure 3.8 shows how the wind speed correlations decrease between geographically distant locations. Larger balancing areas will increase the potential area from which renewable generation can be drawn, and therefore lower the overall variability of total renewable output.

Reserve Sharing

Balancing areas may also choose to cooperate through other mechanisms besides full consolidation. One way that they may reduce the costs of variable generation integration is through reserve sharing agreements. Under these conditions the balancing areas independently schedule and dispatch generation to meet their own loads. However, since certain types of reserves, such as contingency reserves, are utilized only infrequently they may serve as backup to multiple balancing areas, should sufficient transmission capacity be available.

Dispatch Intervals

Another means by which markets may reduce the effects of system variability is through the use of more frequent market operations than the typical 1-h period for dispatch. Sub-hourly balancing markets aid in the integration of renewable

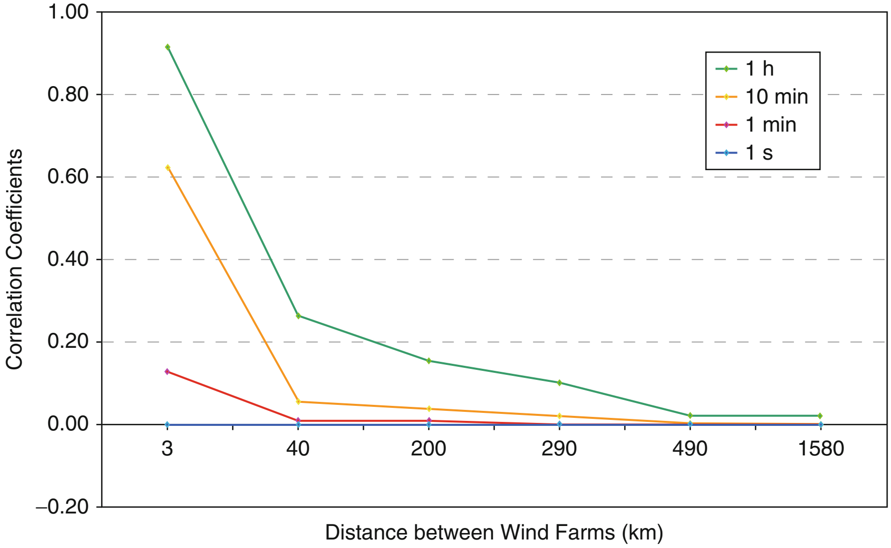

Fig. 3.8 Wind speed correlations with distances between locations in the United States [14]

generators by enabling the utilization of existing flexibility in the system and reducing the requirements for ancillary services. In addition, they allow the renewable generators to revise their production forecasts closer to the operating period to minimize forecast errors and thus imbalances.

Ancillary Service Markets

Ancillary service markets will play a key role in the integration of high levels of renewable energy resources. However, the current services offered may not be sufficient and new services should be created based on power system reliability requirements. For example, load following is an important system function with large amounts of renewable generators due to the increased system variability. While this is currently supplied through other units in the energy market, at high renewable penetration rates a market for fast ramping resources may prove to be advantageous. Another key consideration is the adoption of varying ancillary service requirements in response to current renewable generation conditions. When the amount of wind power currently being produced is high, the securing of large amounts of load following reserves would be wise, should a significant decrease in wind power output occur. However, when the wind power output is at a low level, the need for load following reserves is significantly decreased. By co-optimizing not only the choice of ancillary service providers with energy providers, but also the amount of ancillary services, the cost of variable generation integration can be reduced.

Capacity Markets

Well functioning electricity markets are required not only to supply the necessary amount of energy to meet demand at each point in time, but also to supply the generating capacity necessary. The calculation of the capacity credit for variable generation is one of the most contentious issues related to renewable integration, with many different methods being utilized in different systems [15]. Since a capacity credit is normally based on a system reliability measure, such as loss of load probability, it is effectively a measure of a units contribution to system reliability. Since the need for reserve capacity is highest at times of high system stress, when a loss of load is most likely to occur, capacity credit measures value available capacity at these times as more valuable than at times with a low probability of unserved load. Variable generators have a lower capacity credit than all but the most unreliable of conventional generators due to their high effective forced outage rate. These high effective forced outage rates are the result of weather-induced unavailability and not generator failures. Since the correlation between wind power output and peak load is weak in most locations wind generators tend to have fairly low capacity credit, as the timing of the capacity availability is so critical in the credit determination. On the other hand, solar generators tend to have relatively higher capacity credits, despite their generally lower overall capacity factors. This is due to the fact that the most regular instances of high solar output correspond to the same times as peak demand.

Locational Marginal Prices

Variable generators generally have high capital costs, but low variable costs when compared with conventional generators. The practical implication is that variable generation units will have lower marginal costs of production (often bid as zero) that they may submit as bids into energy markets. When the amount of variable generation is sufficient to remove the highest bidding unit that would otherwise be producing, the market cost of energy at that point in time is reduced. This reduces the total revenue collected by all generators and thus total system costs. Transmission system congestion leads to different prices at different nodes in the system, known as locational marginal pricing (LMP). When government policies for renewable energy production, such as production tax credits, are combined with very high renewable output at a particular point in the transmission system, the possibility of negative LMPs arises. In this case the production incentives offered make it economically efficient for units to pay to produce electricity. This situation is not sustainable in the long-term, neither for the variable generator nor for conventional units in the same area. If this situation occurs at a high enough frequency it could lead to the decommissioning of conventional units in the area, to the detriment of system reliability that relies on those units for reserve capacity [16].

Transmission Planning

The sites that offer renewable generation sources the highest capacity factors are often located far from load centers. This dictates that new transmission must be built in order to utilize these areas with high renewable resources. While the need for new transmission is easily identified the process times for permitting and construction of the transmission often exceed those for the siting and construction of renewable generation. This can lead to situations where large amounts of renewable generation cannot be utilized because of transmission bottlenecks.

Transmission planning is not only important for gaining access to renewable resources, it can also be important in helping to integrate large amounts of renewable generation into the electricity system. Additional transmission between balancing areas or interconnects can allow for better utilization of renewable generation by providing alternative outlets for generation above what can be utilized within the local area. Having strong transmission ties between areas is a critical element in taking advantage of the geographic diversity of renewable resources. When the current renewable generation is low in one area but high in another additional transmission allows this energy to be utilized instead of curtailed. One proposed project in the United States that plans on utilizing increased transmission to aid renewable integration is the Tres Amigas project [17]. The North American electricity grid is split into three essentially independent interconnections: the Western, the Eastern, and Texas. The Tres Amigas project aims to provide expanded transmission links through the addition of 5 GW DC superconducting lines between each of the interconnections. The proposed site on the border of New Mexico and Texas is located close to areas of excellent wind and solar resources.

An even more ambition project for the integration of vast renewable resources over a large geographic footprint is the DESERTEC project [18]. This project aims to create a supergrid throughout Europe, the Middle East, and North Africa. This supergrid would open access to a larger number of renewable resources, including concentrating solar electricity from the Middle East and North Africa and wind power from Northern Europe. The enormous footprint of the project would ensure a smoothing of the renewable generation sources and demand sinks.

Enabling Greater Renewable Penetration

Just as there are currently a number of generation technologies utilized to fulfill electricity supply, there will be a number of technologies and strategies needed in order to enable the inclusion of larger amounts of renewable generation into the electricity system. Figure 3.9 shows a conceptual cost ranking of different demand and supply side technologies and systems that provide the electricity system with additional flexibility, and thus can help in the integration of variable generation. The inclusion of a number of different renewable generation technologies, with

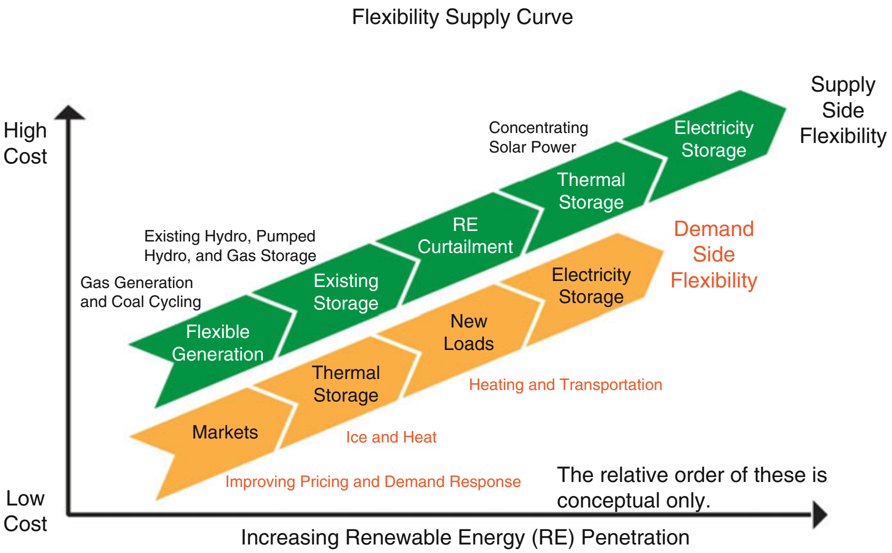

Fig. 3.9 The flexibility supply curve shows a number of different methods of providing system flexibility that may be useful in integrating renewable generation sources [19]

complementary generation characteristics, in future capacity expansion will also help to facilitate operating a high renewable electricity system. Dispatchable renewable sources, such as geothermal, biomass-fired thermal and hydroelectric plants, are able to contribute to renewable generation goals without significantly altering system operations. Geothermal and biomass-fired plants can serve as baseload units that reduce the amount of variable generation necessary at all times. Hydroelectric units can also serve this function, but may better serve the system by providing load following capabilities for variable generation due to their quick response times. However, the limited geographic potential and/or economic costs of these plants dictate that large capacities from variable sources will also be required to meet high renewable penetration goals. A number of different strategies for mitigating the effects of these plants' variability and uncertainty are described in what follows.

Variable Generation Forecasting

Renewable generation is both variable and uncertain; however, the uncertainty is a much more critical factor than the variability. If the variable output of renewable generation was known in advance the impact would be considerably reduced. The variable output could still be scheduled in a normal unit commitment and dispatch system, and would in fact be dispatchable. It is the uncertainty associated with renewable output that is most troubling. Thankfully, the future output of a variable generator is not completely random at smaller timescales, due to the fact that it is weather-driven. Forecasting techniques can be used to estimate the future output and this information can be incorporated into future generation plans. However, forecasting results tend to improve with reduced lead times between making the forecast and the time of realization. The inaccuracies associated with forecasting at longer timescales, in conjunction with the long start-up times of baseload units, diminishes the practical impacts of wind forecasting in particular. Numerical weather prediction models are commonly used to make wind forecasts for the day-ahead unit commitment process. Further improvements to these models, and their use at smaller geographic distances, has the potential to improve the utilization of variable generation through better forecasting.

Stochastic Planning and Operating Tools

One way in which variable generation forecasting can be better utilized is through the use of stochastic unit commitment and economic dispatch models. Instead of a simple point forecast these models incorporate a number of different scenarios of variable generation power output, with associated probabilities, during the future time frames under consideration. Through their explicit consideration of the stochastic nature of the variable generation these models are able to produce more robust schedules that can respond more easily to the different possible variable generation scenarios. The more robust schedules produced tend to produce lower average system costs than those that utilize only a point forecast [20]. Improved forecasting that considers not only the most likely value for the next time point, but also a consideration of the range and likelihood of possible values will increase the impact of stochastic operating tools. For this reason the consideration of the distribution of forecasting errors for variable generation production is important as it can inform the creation of more realistic forecasting scenarios. Improved stochastic programming algorithms that reduce the computational time necessary to solve for an optimal schedule will also increase the effect of these tools by allowing for the consideration of a larger number of scenarios and their application at smaller timescales.

Faster Markets

As the time between the forecast of variable generation and the actual production time decreases, so does the average error of the forecast. For this reason the implementation of faster dispatch markets can help lead to further renewable generation penetration as it decreases the costs associated with variable generation uncertainty. By having less time between the time of forecast and the actual time of output, more current information can be utilized in deciding the forecast. Since day-ahead markets followed by 1-h dispatch market tend to be the normal historical system of market operation, sub-hourly markets are necessary for further improvements. These sub-hourly balancing markets also provide another means by which the regulation and load following reserve impacts of variable generation may be reduced.

Demand Response

Another possible approach to incorporating larger fractions of renewable generation into the electricity system is known as demand response. This approach is based upon changing one of the main tenets of traditional electricity system operation: varying generation to match an uncontrollable load. Demand response gives the system operator control over the timing of some portion of load by allowing blocks of load to be delayed. This approach has traditionally been used by system operators as a last resource during times of very high peak loads. Large industrial loads often structure their contracts with utilities so that they receive either payments or lower base rates for allowing the utility the privilege of interrupting their service periodically, up to a maximum number of occurrences. Industrial customers are preferable from the utilities' perspective because they allow a large reduction in load through a single customer interruption. Large commercial installations also have the possibility of participating in demand response programs, as the heating or cooling of a large commercial building could be a significant resource.

The adoption of "SmartGrid" technologies has the promise of allowing residential customers to also participate in demand response programs. Unlike industrial loads, individual residential customers are a very small percentage of the total system load. However, if the utility can simultaneously control a large number of large-load distributed residential appliances, such as air conditioners, the aggregated effect can be comparable to the response provided by a large load industrial customer. It is important to note that demand response programs do not significantly reduce total electricity usage, instead the load is shifted from times of high demand, when additional generation may be unavailable, to periods of lower demand. Household demand response is limited by cost to large appliances, and by consumer acceptance to appliances whose usage patterns are somewhat time insensitive. For example, a refrigerator's load can be postponed, but only for very short timescales, so that the contents do not spoil. On the other hand, a dishwasher turning on can presumably be delayed until the total demand levels fall at night, with far less negative effects to the consumer. In the extreme case one can imagine the linking of certain appliances' usage to the current level of variable generation output. A related idea is the use of time of use pricing for residential electricity, as opposed to the flat-rate (or limited peak/off-peak split) rate structure that currently prevails.

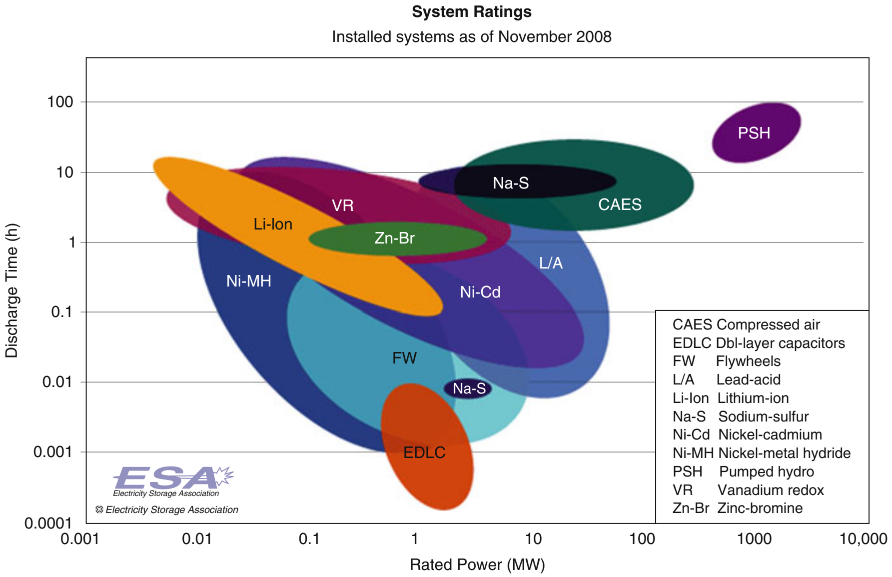

Fig. 3.10 The range of power and energy combinations available for different storage technologies

The most troublesome aspect of time of use pricing is the limited ability or desire of residential customers to react to different prices. For extensive changes in residential usage patterns the time of use pricing scheme would need to be paired with meters that can be programmed to adjust appliance usage patterns based on the current price of electricity.

Electricity Storage

A commonly proposed solution to mitigate the effects of renewable generation variability is the use of electricity storage. There are a number of different technologies that could be used for such purposes, with each technology operating most efficiently over a range of timescales and power and energy levels. An illustration of the effective ranges for different technologies can be seen in Fig. 3.10. There are three basic timescales on which electricity storage is needed, based on response duration: very short duration, short duration, and long duration. Generally speaking, the longer the timeframe is, the higher the associated energy requirements are. These types of storage can also be classified according to their application, where power quality, bridging power, and energy management correspond well to very short, short, and long duration timeframes, respectively [21]. Very short duration storage is needed to respond on the millisecond timescale and provide large amounts of power for a matter of seconds. This type of power is important for power quality and frequency regulation applications. Requiring a response on the multiple second to minute timescale is short duration storage, used for bridging power. This type of storage is useful in the role of generation reserve, and similar applications, to provide power in the event of a system contingency. Very long duration storage can respond on the multiple minute timescale and is used to provide power over long durations, such as those needed for load leveling applications.

While both bridging power and power quality applications are important considerations in integrating variable generation, storage technologies with large rated power output and long discharge times will be the most important for large penetration rates of renewable generation due to their ability to shift energy from times when variable output exceeds demand to those where demand is greater than variable output. Pumped hydroelectricity is one large-scale technology that is applicable for long timescales. During times of excess generation the pumped hydro facility can transfer water from a lower reservoir to a higher reservoir and utilize the potential energy gained during times of high demand. Pumped hydroelectricity storage is somewhat limited by geographic considerations; there must be a fairly large height difference between the two reservoirs, ruling out very flat locations. Compressed air electricity storage is also limited by geographic considerations, particularly for systems with long discharge times. This is due to the fact that very large systems rely on caverns as the compressed air storage vessel. In these systems excess power is used to compress air into a storage area, where it can later be expanded to produce electricity when desired. Current systems use natural gas combustion to supplement the storage compressed air, but designs for future systems need to include this option. Chemical storage in the form of batteries is another possible solution. Lead acid batteries are currently a cost-effective solution, but are also a very mature technology that have relatively low roundtrip efficiency and are limited in grid applications due to their relatively short lifetimes. Sodium-sulfur (NaS) batteries have long cycle life, relatively high efficiency, and are used primarily for grid applications due to the high operating temperatures. A number of other battery chemistries are also available, from those such as lithium-ion that are seen in many other applications where portability is essential, to technologies such as redox flow batteries that are exclusive to large-scale power applications.

Figure 3.11 shows the effect that electricity storage can have on efficient system operation, in terms of reduced wind curtailment, in a theoretical completely flexible system. As may be seen, even a relatively small amount of storage can greatly increase the potential renewable penetration rate by reducing the amount of variable generation that must be curtailed, thus improving the economic viability of additional variable generation capacity. Additional amounts of energy storage can aid in the integration of renewable generation, but provide diminishing marginal returns. Currently electricity storage options are fairly expensive, limiting their potential applications. Even if significant cost improvements in storage technologies are realized, electricity storage should be viewed as but one tool to aid in renewable generation integration.

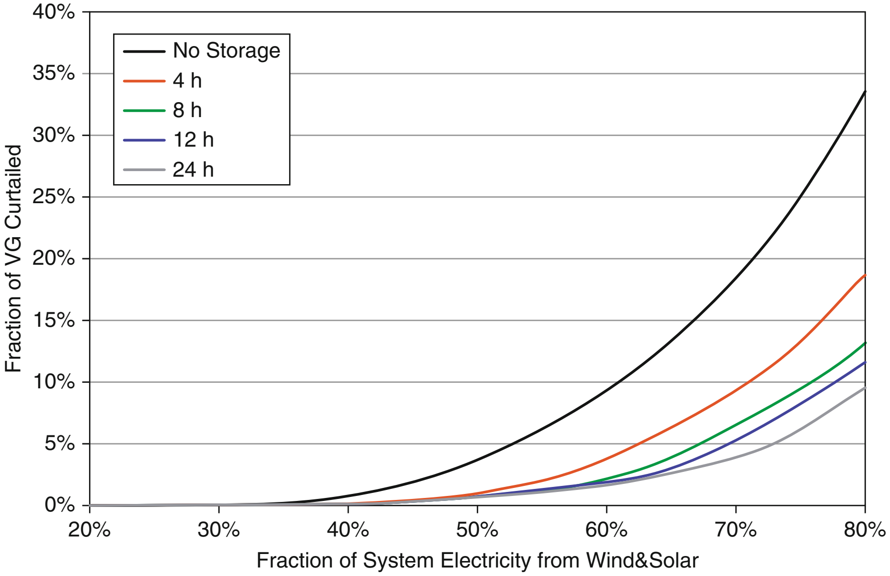

Fig. 3.11 Total curtailment as a function of VG energy penetration for different amounts of energy storage. Assumes 30/70 solar/wind mix, 12 h of storage, and a 100% flexible system. Each hour of storage represents 1 h of average system demand [19]

Renewable Generation Curtailment

Another solution that is occasionally used, even at the current low levels of renewable generation penetration, is production curtailment or spilling. If the production from variable generation is so large that it affects the operation of other units, such as putting baseload production below minimum generation levels, or reaches physical constraints, such as transmission line capacities, then the production can be temporarily halted. While this is a simple solution for small amounts of variable generation, it has its limits of applicability. These are often economic, in that excess variable capacity can be built that will only produce energy at a very small number of needed time points, and will be curtailed during the rest of its possible production times. This would significantly affect the economics of the variable generation plant at very high levels of curtailment, making it economically inefficient to build further capacity unless the load production schedule is expected to be anti-correlated with other variable generation locations.

New Loads

The peak and trough cycle of daily electricity usage requires the use of different types of generation in order to maintain system flexibility. However, the system would be able to operate more efficiently if the daily usage profile was more flat and baseload generators could provide a larger fraction of total energy. This would require sources of new load whose usage patterns coincided with the current nightly trough. In the same vein, since wind power output is generally higher at night, new nighttime loads would allow for less wind curtailment as there would be fewer situations where wind plus minimum baseload generation exceeded the current demand. The most commonly named source of a new load that can serve these purposes is the electric vehicle. Most vehicle usage occurs during the day, leaving vehicles idle during the night. For electric vehicles this provides the opportunity to charge and have their full range capabilities in time for the owner's use in the morning. The charging pattern that the vehicles follow is very important in ensuring that they flatten the load profile, instead of increasing peak loads [22]. To this end, policies must be put in place that can benefit the electricity system without disturbing the benefits that consumers derive from the vehicles, and thus blunting the rate of adoption. One extreme example of a policy intended to derive the most system benefits from the vehicles is the idea of utility controlled charging. In this case the utility would be able to use the vehicles as a form of demand response, perhaps providing an outlet for variable generation that might otherwise be curtailed.

Flexible Generation

The current electricity generation portfolio was not designed with the incorporation of variable generation resources in mind. Very high levels of variable generation penetration will most likely require more flexible accompanying generation, in order to help compensate for the non-dispatchable output. Generator flexibility includes the ability to both start and ramp quickly. For example, current inflexible nuclear and coal plants can require hours to ramp up from a cold start to full capacity. On the other hand, simple cycle natural gas turbines are an example of a unit that can start quickly and ramp from minimum generation levels to full capacity quickly enough to be used to compensate for generator outages. While these flexible units provide the system operator with more dynamic options for meeting the load, they also tend to be more expensive than inflexible baseload plants. However, the current level of system flexibility is not fixed. As older inflexible units reach the end of their operating lives and are retired, new more flexible units can be brought online to replace them. The impact of system flexibility on the integration of variable generation is shown in Fig. 3.12. Here flexibility is represented solely by the combined minimum load levels of all generation units in the system. The ability to integrate variable generation is represented by the amount of available wind generation that must be curtailed as a percentage of the fraction of the total system energy provided by wind power. As may be observed, increased system flexibility causes the amount of wind generation curtailment to drop significantly.

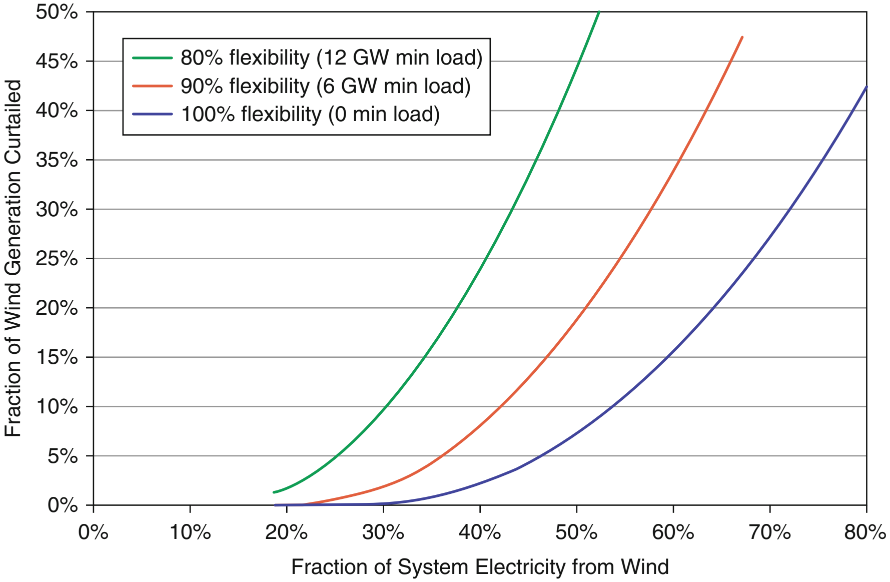

Fig. 3.12 Total curtailment as a function of usable wind energy penetration for different system flexibilities [19]

Future Directions

Variable generation penetration rates are still relatively low (below 10% by energy) in most large systems. At these lower levels variable generation can be fairly easily incorporated into existing electricity system operations. However, if global trends persist very significant penetration rates will soon be reached. At high penetrations of variable generation significant restructuring of current system operations could be necessary to accommodate the additional system variability and uncertainty. As many electricity systems reach penetration rates of between 15% and 30%, methods of economically and reliably integrating variable generation sources will start to be tested on a daily basis. This will quickly bring attention to issues that were not properly considered in previous integration studies. Potential operating issues at higher levels of variable generation must be anticipated before these higher levels of renewable penetration are realized in order to maintain system reliability. The electricity system is such a vital part of daily life that even small changes in the reliability of the system would have far-reaching economic and societal consequences. Further work is required in many areas of renewable generation integration. Resource assessment of wind and solar resources can lead to better decisions on where to site new generation capacity to maximize not only power output, but the benefit to the system. Technological development of generators can both reduce system costs and allow for variable generators to interact more smoothly with the traditional system operation paradigm. Further work on the characterization of variable generators is necessary to understand how systems with large penetration rates will behave. Finally, extensive work is necessary in the area of system operations. Understanding the ability of both supply and demand technologies to increase system flexibility will be critical, as will new ideas on the structure of systems with large amounts of variable generation.

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