Powering into the Future

RENEWABLE ENERGY & GRID RELIABILITY

ACKNOWLEDGMENTS

The following report was prepared by M.J. Bradley and Associates. The authors are grateful for the valuable contributions, critiques, and insights of the following industry experts: Mark Ahlstrom, Michael Goggin, Carl Linvill, David Littell, Sierra Martinez, Kate McCormick, Terri Moreland, Brian Parsons, Phil Pettingill, Mark Rothleder, Kelly Speakes-Backman, and Kevin Steinberger.

The review and comments related to this document are not, and do not imply, an endorsement of any of the statements or findings expressed herein. Reviewers are not responsible for any content within the report. The findings and conclusions in the report are those of the author(s) and do not necessarily represent the views of the reviewers.

FEBRUARY 2017

CONTENTS

Reader’s Guide

In the Great Plains, the Southwest Power Pool set a record in early 2016 by using wind to meet 49 percent of power needs. In California, renewables often served the majority of state electric needs in 2015, with the state recording one new high after another for the amount of solar connected to the grid. And in Colorado, 71 percent of the electricity on the largest utility’s power grid was provided by wind one morning in the fall of 2015.

Wind and solar are the fastest-growing sources of electric power—growing, on average, a staggering 14 percent per year between 2009 and 2015—and accounted for 61 percent of all new capacity added in 2015. Yet these resources have significant room to grow. Renewables (excluding large hydroelectric generators) currently contribute only about 7 percent of total U.S. electricity generation. They are likely to get a boost as their costs continue to fall and policymakers increasingly see these clean energy resources as a vital tool in the fight against climate change.

Generating increasing amounts of electricity from renewables can offer significant benefits to our health, environment, and pocketbooks. But it also presents challenges. The grid is a complex, interconnected system of power plants, electricity consumers, and the transmission and distribution systems that connect them all. We hope the following pages will help readers better understand this complexity and put it into the broader context of maintaining grid reliability.

Among other things, reliability means preserving balance between the second-by-second changes in electricity supply and electricity demand. Federal, regional, and state regulators, grid authorities, and utilities use power generators of all types, as well as other devices, to maintain this balance and keep a healthy frequency and voltage on the grid. While the variability and weather-driven changes in output of renewable resources are not in and of themselves problematic, these characteristics are helping to reveal a potential weakness in the future electric grid: a lack of sufficient flexibility to manage consistently high levels of renewable energy. A future, cleaner grid will need more flexibility and responsiveness to address changing sources and characteristics of generation and demand.

Renewable energy has moved beyond what many once saw as an uneasy coexistence with coal, gas, and nuclear power to a more multifaceted and more thoroughly integrated role in which these technologies provide essential reliability services similar to those from conventional thermal facilities.

The purpose of this report is to draw from the thousands of pages of existing technical and policy literature to highlight the key principles of reliability and how renewables fit into this picture. Understanding the role renewables can play in maintaining a reliable grid requires an understanding of existing reliability measurements, requirements, and regulations. Chapter 1 of this report provides this background. Chapter 2 turns to renewable resources—in particular wind and solar—and the ways in which grid operators are integrating these resources into the grid. Finally, Chapter 3 details the growing ways in which wind and solar generators can contribute to specific grid reliability needs, by providing capacity, controllable generation, and frequency and voltage control. Chapter 3 also explores how characteristics unique to wind and solar generators can improve the flexibility of the grid and contribute to resiliency and reliability. Each chapter can be used as a reference separately from the others, or used in conjunction with the others to form a broader picture of renewables in the reliability space.

Throughout this report, we've provided a number of sidebars and callouts that provide additional detail and background on important technical topics. We also have boldfaced key terms that are defined in an easy-to-reference glossary at the end of the report. We hope this maintains the focus on the key reliability issues at stake while helping to guide those readers less familiar with the electricity world.

Renewable energy has moved beyond what many once saw as an uneasy coexistence with coal, gas, and nuclear power to a more multifaceted and more thoroughly integrated role in which these technologies provide essential reliability services similar to those from conventional thermal facilities. Ultimately, as wind and solar power levels increase, utilities, grid managers, and regulators will continue to ensure that systems have the right mix of resources to provide the full suite of reliability services necessary to keep the grid functioning. Renewable resources will be an important part of this reliability mix.

1. Reliability: Second by Second, Year by Year

The power grid is a complex, interconnected system of power plants, electricity consumers, and the transmission and **distribution systems** that connect them all. Nationwide, over 7,300 power plants (or **generators**) with a combined capacity of 1,060 gigawatts power over 145 million homes and businesses across the U.S. The current power supply is supported by 642,000 miles of **transmission** lines—enough to circle the globe 25 times—and 6.3 million miles of **distribution** lines.[1] Even rooftop solar and other consumer-owned power resources are part of this system and connected to the power grid.

The balancing of electricity supply from power plants and demand from consumers is dynamic and changes by the second. Because electricity is still difficult (or costly) to store in amounts high enough to serve large numbers of consumers, electric generation must generally match the electricity demanded by consumers at the exact moment of use. Disruptions in this balance can harm the grid and cause service outages (see "Measuring Electricity: The Basics" on pages 6–7 for more detail on how the **reliability** of the grid is measured).

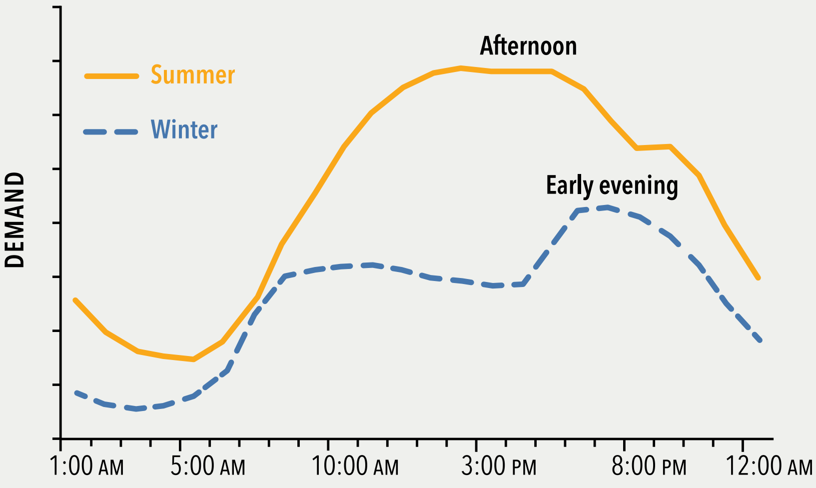
Many factors stress this delicate balancing act and complicate efforts to maintain operational reliability. Under normal grid conditions, the largest factor that must be addressed is changes in electricity demand.

Electricity **demand** is the amount of electricity being used by all consumers at any one time. Consumers don't tell grid operators before they switch on a hair dryer—nor do large factories before increasing production—but the system must have power plants ready to quickly respond to any such jumps in its electric **load**. Utilities and system operators conduct short- and long-term forecasts that help them anticipate conditions affecting system demand, such as hot summer days (that drive up air-conditioning load), upcoming holidays (that reduce commercial and industrial demand as more people stay home), the Super Bowl (when millions of TVs tune into the game), or changes in economic conditions (since different customer types have different electric requirements).

DID YOU KNOW?

We use stored electricity every day, such as in the battery that runs your phone or starts your car. Storage on a scale large enough to power an entire home—or city–is now starting to join the grid. Grid-level storage has been in place in limited amounts at pumped hydro facilities that use electricity to move water uphill, where the energy is stored as potential energy behind dams. The water is then released during peak demand periods to flow downhill through hydroelectric generators. New storage technologies include: larger chemical batteries; compressed air facilities that store air under high pressure, releasing it on demand to spin a turbine; and flywheels, which are large rotating masses in very low-friction environments that store kinetic energy (the energy of motion). For more information on energy storage, see the sidebar on Storage as a Grid Reliability Tool (page 22).

Figure 1. Illustrative Seasonal Demand Shapes



A region’s daily **load shape** is an element of maintaining the balance of supply and demand. As load changes throughout the day, sometimes with periods of rapid change, the system requires generation that quickly can **ramp** (change electrical output). The load shape often has a seasonal dimension due to different heating, cooling, and lighting requirements across different times of year. For example, in New England, the **peak**, or highest demand, in summer occurs in the afternoon when air-conditioning is running full blast. By contrast, in the winter, New England peak demand occurs in the evening, when more lighting is used on the shorter winter days.

DID YOU KNOW?

Climate and other natural forces can pose both long-term and immediate risks to the electric system. These forces complicate both system balancing and infrastructure operation and maintenance. Electric utilities and grid operators have contingency plans in place for weather emergencies such as wildfires and thunderstorms, but they can still cause serious issues that last multiple days on very short notice. On a more long-term scale, one of the largest hazards to electric system reliability is climate change itself, which brings increases in severe weather and environmental events. Drier weather in some areas has also caused droughts, leading to shortages in hydroelectric power that has historically served large portions of West Coast load. Additionally, rising temperatures increase demand for electricity for air-conditioning and other cooling, which can cause peak demand to spike and place additional strain on grid systems. At the same time, higher air and water temperatures caused by climate change reduce the efficiency of power plant cooling, which lowers total output of generators and can increase the risk of partial or full shutdowns of power plants, resulting in a decrease or total loss of crucial grid services when they are most needed.

A MODERN GRID

As the electric grid grew across the country, it was structured around a centralized power system, where energy was generated at large plants owned by utilities and then transmitted out through power lines, often traveling long distances to reach the consumer. In some ways, especially in the West, this grid looks like a large wheel, with generators at the hub and spokes leading to consumers around the rim. However, as energy sources are increasingly distributed throughout the system and interspersed with consumers, the grid more and more resembles a web. This is changing the way that the grid is managed and operated by shifting the direction of power flows on lines, emphasizing the need for new and advanced lines as well as increased coordination among generators, transmission and distribution system grid managers, and consumers.

Additionally, the development of the **smart grid** is improving control of the grid and the ability of system operators and consumers to monitor energy use. More control allows operators to send nearly instantaneous signals to smart grid equipment, generators, and even sources of demand to adjust operations, leading to better reliability outcomes and lower operating costs. **Visibility** helps system operators better plan for and rapidly respond to grid conditions by allowing them to see how facilities are operating in real time and how consumers are using electricity. In the old grid, to know how much to charge consumers, utility workers would visit every customer to manually read a meter that had ticked off kilowatt-hours over the course of the month; if a neighborhood distribution line went down, a utility was dependent on a customer calling in to report a loss of power in order to be aware of the issue. With smart grid capabilities, utilities can instantly know the exact location of outages; utilities and customers can track usage on a minute-by-minute basis. These capabilities—and many more—have reduced system losses and electricity costs.

The smart grid and other tools can help improve visibility of renewable generators (especially those that are distributed among consumers), increase data that can be used for forecasting renewable output, and improve the ability to use demand-side management to respond to changes in renewable output. So far, at least 25 states have implemented policies to adopt smart grid technology, seeing it as an opportunity for a more secure energy future.[2] As climate change poses a greater risk to the grid by bringing more extreme temperatures and intense weather events, smart grid technology also can help maintain reliability by enhancing communication and response throughout the system.

Electric utilities, system operators, and third-party developers are making significant investments in the grid to modernize infrastructure, increase flexibility, and support ongoing changes to the electric power system. According to the Edison Electric Institute, investor-owned utilities alone invested about $73 billion in transmission infrastructure from 2010 through 2014 and are likely to spend another $85 billion from 2015 through 2018.[3] A Brattle study expects investments in transmission upgrades and additions to be in the range of $120–160 billion per decade through 2030, $25–40 billion of which will be driven by increases in renewable energy development.[4] Already, a number of projects to add transmission capacity to the system are underway, either under construction or in the planning process. As of January 2014, 5,281 miles of transmission lines were under construction, with an additional 16,599 miles of transmission lines slated to be completed by 2019.[5]

While grid operators primarily manage the grid under normal conditions, they must also plan for external stressors and emergencies. These include:

- **FAILURES OF ELECTRICITY DELIVERY INFRASTRUCTURE:** Lines, poles, and substations are all subject to physical hazards ranging from trees to motor vehicle accidents. Also, as the sidebar "A Modern Grid" (page 3) explains, much of the nation's power lines and other transmission and distribution infrastructure needs repairs and upgrades. Its poor condition exacerbates reliability challenges in some areas.

- **FAILURES OR OUTAGES OF POWER PLANTS:** Power plants face the risk of emergency shutdowns for many different reasons, including equipment failure, fuel shortages, and transmission failures. Under normal operations, in addition to these unanticipated events or "unplanned outages," power plants and other equipment must undergo maintenance and repairs during planned outages (periods in which they cease operation). These outages must be carefully scheduled to ensure that enough power plants and lines remain operating to serve load.

- **NATURAL FORCES:** In addition to creating changes in demand, weather such as high winds and lightning can take down critical infrastructure with little warning; natural disasters such as wildfires, hurricanes, blizzards, and earthquakes can knock out power for thousands or even millions of consumers in a matter of minutes.

- **SECURITY:** Because the country relies so heavily on electricity for daily living, commerce, communication, and transportation, critical components of the electricity system could be targeted for attack. Physical security at many key points in the system protects against these assaults, but emerging threats, such as cyberattacks, pose new concerns as the grid becomes more digitalized and integrated.

In the face of these challenges, utilities, grid operators, and regulators work together to maintain a highly reliable grid. What exactly does that require? Operationally, a range of reliability services are necessary, from rapid response to correct voltage or frequency deviations to long-term resource adequacy and capacity needs. These services are then coordinated and dispatched so that together they maintain a balanced grid.

Reliability Services and Requirements

Both generation and demand can provide grid reliability services. The majority of power plants on the grid today use heat from coal, gas, uranium, biomass, or geothermal energy to produce steam or other expanding gas to turn a rotating mass—a **turbine**—at high speed to generate electricity. Large-scale "concentrating solar" plants use mirrors to concentrate the sun's heat to produce steam to drive the turbine, while wind plants use aerodynamic lift on the blades from moving air (wind) to spin the generator inside each wind tower. Rooftop and other solar panels, in contrast, convert the sun's energy to electricity in photovoltaic (PV) panels; there are no moving parts. Electricity consumers themselves increasingly provide important reliability services as well through flexible **demand response** that can help reduce demand at key moments.

At all times, these resources must balance supply and demand while maintaining the frequency and voltage levels of the electricity throughout the system.

DID YOU KNOW?

Demand response programs allow customers to contribute to the balancing of generation and load on the grid. Instead of generators *increasing* output to meet increased demand, electricity customers in demand response programs are paid to *reduce* their electricity consumption. In some organized markets, demand response is offered into the market in ways similar to generator offers, and the market picks the lowest-cost resource, whether it is more generation (increased supply) or demand reductions, to balance the system.

Ensuring Sufficient and Flexible Generation

Maintaining precise balance between generation supply and consumer demand is essential in maintaining reliability: if either generation or demand outweighs the other, the system becomes imbalanced, placing it at risk of a grid disturbance. This balance requires both adequate quantity and **flexibility** of generation.

Adequacy

The system must have adequate capacity (including distributed energy resources where present) to meet demand at any given moment. The sum of the capacities of every resource (generation, demand response, and storage) that contributes to meeting critical periods of demand on the system (or reducing that demand) must be sufficient to meet the system's total requirements. This necessitates long-term planning to be sure that adequate resources are developed and online, which can take years. Sufficient transmission also must be planned and built to deliver power to consumers. Grid planners also include a buffer of extra capacity—a **reserve margin**—which makes sure that even if a large generator goes down or a particularly intense heat wave rolls through, there will be enough capacity online or readily available (and enough alternative routes of delivery open) to serve demand. The default reserve margin is 15 percent above the forecasted peak demand, although different grid regions often calculate their own reserve margins.[6]

Flexibility

On a day-to-day scale, resources must be able to collectively adjust their generation (or demand) such that load and supply are balanced as frequently as every four seconds. It is especially important that an increasing portion of resources be able to ramp their output up or down. Some ramping needs can generally be planned for—for instance, electricity needs increase every morning as people begin their days—while other changes in the balance of demand and generation must be satisfied in real time, on a minute-by-minute or second-by-second basis. Even on a system with significant amounts of wind and solar, most of these unplanned changes are from the uncertainties of short-term demand forecasts. Variations in renewable energy forecasts and normal **variability** of wind and solar output due to local changes in cloud cover and wind speed can also contribute to the normal changes that must be balanced. The system operator must retain some flexibility as part of standard operating practices to cover the range of these common changes. As variable and uncertain resources increase, additional flexible resources may be necessary to balance the system.

Other changes arise from events such as the sudden loss of a large generator or a major transmission line. Special **contingency reserves** are kept ready to deal with such disturbances. Contingency reserves are often split into two groups: spinning and non-spinning reserves. **Spinning reserves** are generation sources that run below their peak output and have the ability to ramp up their output rapidly—within ten minutes—to respond to **contingency** events while continuing to provide reliability services during normal operation. **Non-spinning reserves** are off-line generators that can start up within ten to thirty minutes (varying by region) and are typically used in emergency situations to respond to frequency deviations and further changes in customer demand.

DID YOU KNOW?

"Distributed energy resources" is a broad term that includes resources "distributed" among customers throughout the distribution system. These can include:

- Demand response, which actively reduces load;
- Energy efficiency, which passively reduces load all the time without needing grid operator or consumer instruction;
- Distributed generation, for instance solar panels and combined heat and power; and
- Small-scale battery and other storage, including electric vehicles.

DID YOU KNOW?

Here is an example of reserves in a typical grid region:

PJM Interconnection is responsible for running the high-power grid and maintaining reliability in the Mid-Atlantic and some of the Midwest.

On May 4, 2016, near the end of the spring "shoulder" season between winter and summer, PJM projected a peak load of just over 86 GW. It had 116 GW of capacity available, creating an operating reserve of nearly 30 GW.

On a warmer summer day, August 10, 2015, PJM projected much higher demand of over 120 GW. On this day, the system had available nearly 149 GW of capacity, leaving the system with an operating reserve of 28 GW.[7]

MEASURING ELECTRICITY: THE BASICS

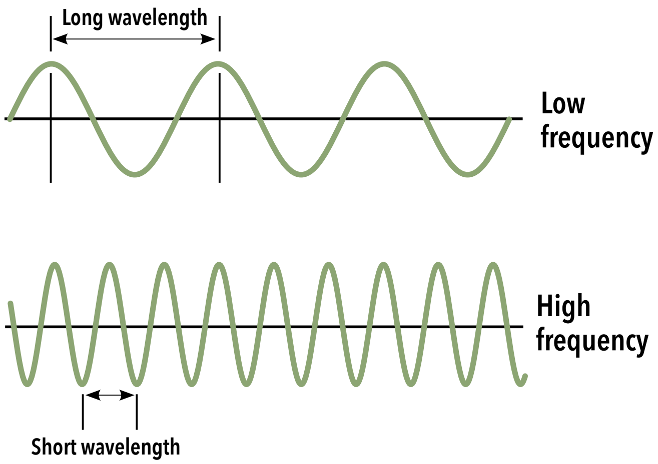
Before one can understand electric reliability, one must understand the basic physical properties that underlie the transmission of electricity. These concepts—current, frequency, voltage, power, and energy—are all ways of measuring electricity as it is generated and passes from one point to another.

First—what actually *is* **electricity**? At its most basic, electricity is the electromagnetic force created when tiny particles carrying an electric charge move along a path. This flow of electricity is called a **current**. Think of water traveling through a hose. The speed at which water travels through the hose is the current. When thinking about electricity, we think of the electrical charges passing through a line or wire, and the current is determined by the rate at which these charges are passing a certain point, measured in amperes (amps).

The electric current that flows through the grid is mostly **alternating current (AC)**, signifying that the electric charge that flows through transmission and distribution wires moves in one direction for some time and then reverses direction (which is a slight but important adjustment to the "water through hose" analogy!). The speed at which a current "cycles" between flow directions is called **frequency**, measured in cycles per second, or hertz (Hz). The standard power frequency for the U.S. is 60 Hz, or 60 cycles per second. This cycling can be pictured as waves where a longer wavelength—the distance between wave peaks—means a lower frequency and a shorter wavelength depicts a higher frequency. On the electric power system, imagine these frequency wavelengths as a spring, where the distance between each coil is maintained at 60 Hz by consistent pressure at both ends—on one end are electricity generators, and on the other end are electricity consumers. If either of these forces loses balance with the other, the spring may become too stretched out (low frequency) or compressed (high frequency), putting stress on the stability of the grid.

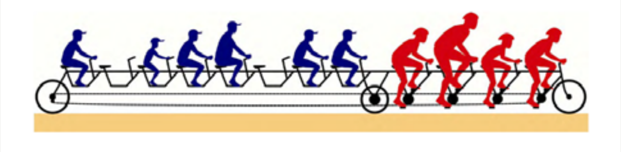
The force driving the flow of electricity is called **voltage**, which is caused by the difference in electrical charge between two points. Generators and transformers can create varying levels of electrical charges. The difference between these charges creates voltage, measured in volts. Maintaining a specific voltage level ensures that energy will continue to flow through the electric system. The greater the difference in charge, the more forcefully energy will be transmitted, or the higher the voltage—the more "pressure" of energy flow. Electricity is produced at one voltage, and then passed through **transformers** that increase the voltage to very high levels, which helps minimize the loss of usable electricity as it passes through transmission lines. The voltage levels needed to run household equipment are much lower, so as the electricity gets closer to consumers, is passes through a series of transformers that lower the voltage to more practical (and safer) levels.

Figure 2. High- and low-frequency wavelengths



Voltage—the difference in charges or "pressures" at various points on the grid—is crucial to ensuring that energy efficiently flows to where it is needed. This is managed partially through the creation and absorption of **reactive power** (as opposed to the "real power" that can keep your refrigerator running—see more on real power and energy below). Many parts of the transmission system—the lines themselves, and components that change the voltage along the way—as well as most electric consumers, consume reactive power. Unlike real power, which can be produced hundreds or even thousands of miles away from where it is consumed, reactive power does not travel very far and must usually be produced closer to where it is needed.

To understand the vital role of reactive power in helping to maintain sufficient voltage, picture the electric grid as a long tandem bicycle, with electricity generators pedaling hard up front and electric consumers sitting without pedaling in back. The speed at which the generators are pedaling is the "real power" being created and pushing the bicycle forward. Now say that one electric consumer leans to a side—this consumer is demanding reactive power. This doesn't slow down the bicycle, necessarily, but if someone doesn't compensate, the bicycle could tip over.



Accordingly, a pedaling generator leans to the other side in order to balance out the bicycle, creating reactive power. Now the system is back in balance, but the pedaling generator can't move quite as comfortably as before. If the pedaling generator must lean too far to either side (i.e., providing or absorbing too much reactive power), this can start to limit its capacity to create real power.

Adjustments in reactive power maintain voltage levels so that real power can flow through the grid efficiently, and this works best if many generators and other resources all do their part. In our bicycle analogy, the bicycle moves forward most efficiently if many of the people on the bicycle help balance the bicycle rather than expecting just a few of them to lean too far.

Finally, the ultimate output and delivery of electricity is described in two ways. **Power** (also called "real" power) is used to describe how much electricity a power plant or energy source produces at any given instant. For electricity purposes, the term **capacity** is used to describe how much power a power plant is capable of producing. In the electricity world, this is measured using watts, and typically represented as kilowatts (kW), megawatts, (MW), and gigawatts (GW); each of these units is 1,000 times greater than the previous (for example, a gigawatt is equal to 1,000 megawatts). About 1,000 homes demand 1 megawatt of power. Generation sources will not always produce output at their maximum power (run at their "full capacity"), as temperature, weather conditions, fuel input, and other variables affect actual output.

Energy, which is the amount of power that is generated over a specific period of time, is measured in kilowatt-*hours* or megawatt-*hours* (kWh and MWh). A megawatt-hour of energy is roughly enough to provide electricity to 1,000 homes for one hour. For example, a natural gas plant with a capacity of 500 MW that operates at this full power level for one hour will generate 500 MWh of energy, but if it runs for only half an hour, it will generate 250 MWh. In terms of our hose example, the diameter of the hose mouth can be thought of as its capacity—the amount it can discharge in an instant under constant pressure—and the total volume of water that flows from the hose over a period of time is its energy.

Source: Leonardo Energy, "Explaining Reactive Power." http://www.leonardo-energy.org/resources/143

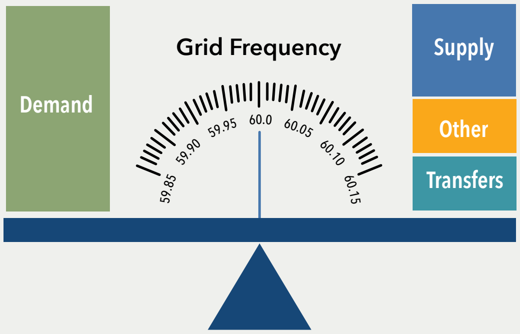
DID YOU KNOW?

In some situations, when load exceeds all available supply, grid operators will "shed" load to stabilize frequency and return the system to balance. Load shedding usually is deliberate and is done through "load curtailment" agreements with customers who agree to pay less in electric charges in return for possible interruptions in service. The goal is to limit service reductions and avoid uncontrolled, cascading outages.

Frequency Control

Grid operators constantly fine tune the amount of supply in the system to maintain a frequency as close to 60 hertz (Hz) as possible. Every one of the thousands of power plants on the grid are collectively synchronized at 60 Hz. Likewise, all grid-connected devices are designed to operate at a 60 Hz frequency (just check the back of any appliance used in the U.S.—it will specify 60 Hz). Not enough supply to match demand, and the system-wide frequency will drop. Too much supply, in contrast, increases the frequency. Precision matters; grid operators worry when the frequency exceeds a narrow control band as small as ±0.05 Hz. Frequency deviations can signal the onset of serious grid disturbances. Events that move frequency 0.5 Hz or more, caused by too many sudden disconnections (especially of generators), downed transmission lines, or other grid failures can quickly result in serious disturbances to grid operations, which can cascade to a full blackout of service. Frequency control keeps these deviations from 60 Hz within manageable levels to avoid such dramatic consequences.

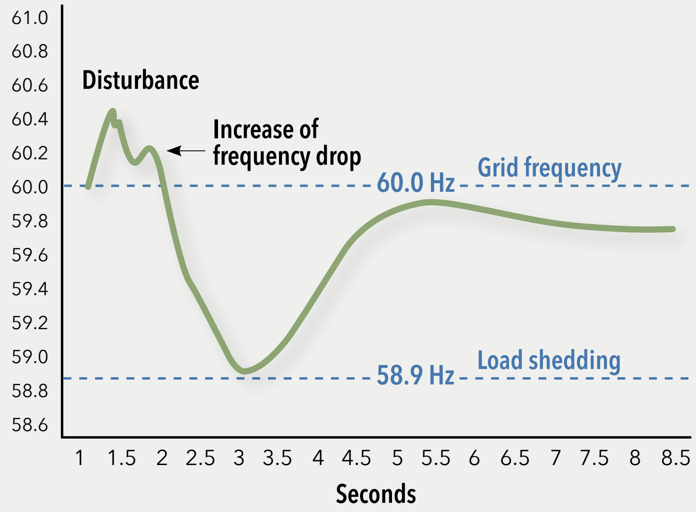
Figure 3. The balancing act of frequency control



Frequency deviations also can harm some motors and other machinery. To avoid such harm, many conventional generators, motors, and equipment have automatic **trip points**, or frequency deviation levels beyond which they will disconnect from the grid. A key part of maintaining power system stability following a frequency (or voltage) disturbance is not only returning the power system to normal, but also ensuring that power plants do not make the problem worse by tripping offline when the disturbance occurs. The failure of generators to **ride through** grid disturbances can lead to a cascading failure and has been a contributing factor in several recent blackouts.

Primary **frequency control** stabilizes frequency (in other words, keeps it from dropping further) after a dip due to insufficient generation—for example, from a sudden power plant outage or a storm that downs several transmission or distribution lines at once—and occurs automatically within a matter of seconds. Automatic **governors** installed on most power plants can monitor system frequency and (if activated) respond accordingly by slightly increasing or decreasing their output. These governors can be thought of as the cruise control on a car that changes in speed and increases or decreases the engine's rpm to maintain a steady speed, except that thousands of governors act collectively to maintain the frequency balance. Demand response also can help to stabilize frequency through measures that lower consumer demand during peak times.

Figure 4. Frequency recovery after a disturbance



This graph illustrates a system response to a frequency disturbance. After an initial rise, frequency begins to rapidly drop. Primary frequency control, including load shedding, kicks in within a few seconds to help restabilize the system. Once frequency is no longer dropping, secondary and tertiary frequency control will bring the system back to 60.0 Hz.

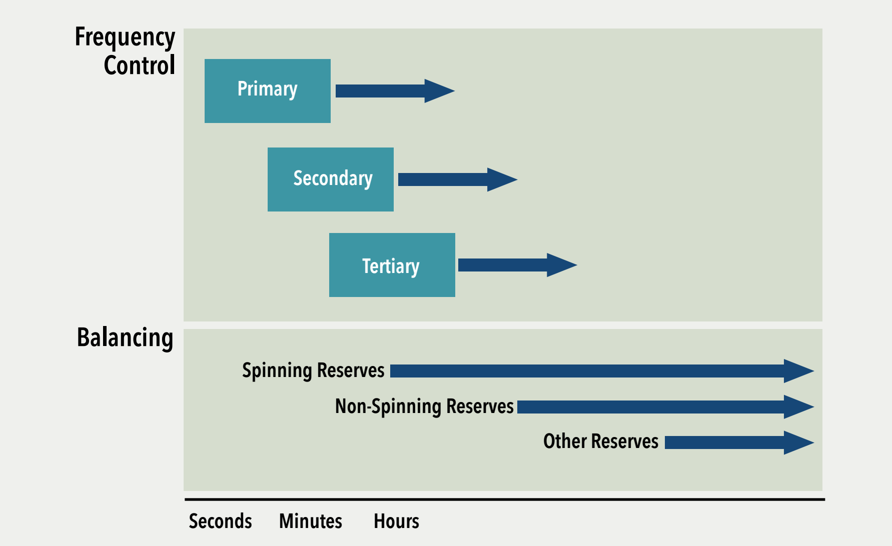
Inertia on the power grid helps to slow the rate of change in frequency when an unexpected event happens, giving governors time to respond and start moving frequency back to its desired level. If you picture the electric system as one interconnected machine powered by many electric generators that are all spinning in sync, the collective spinning mass of all of these spinning generators establishes the total inertia present in the system. If some of the rotational kinetic energy of this spinning mass is converted to electric power in order to meet the current level of demand, this machine will have less inertia and start to slow down (which is why the system frequency starts to fall faster and faster). The less inertia on the system, the steeper the fall in frequency, giving generators less time to respond and stabilize frequency.

Inertia is an inherent attribute of heavy generators and motors, like big steam coal plants, that are spinning in sync with the grid's frequency (and are thus "synchronous" generators). Increasingly, variable renewable generators can also provide extra power in ways that are like inertia and primary frequency response (see the section "Renewables' Reliability Service Value" on page 27 for more detail).

Once frequency has been stabilized, in order to return frequency to normal levels closer to 60 Hz, the system uses secondary frequency control. This usually occurs over a few minutes, though some renewable and other generators are able to respond over faster time frames. Secondary frequency response is triggered by area monitors (people, computers, or a combination of both in centralized control rooms) that send signals to generators to adjust their output (or decrease load, in the case of demand response resources).

Finally, tertiary frequency control is conducted over the following minutes or hours to ensure that the system is prepared to respond to any subsequent frequency issues. This may involve bringing on additional non-spinning reserves that were not previously operating.

Figure 5. Time continuum of frequency control and balancing



Source: NERC

DID YOU KNOW?

The grid utilizes numerous devices to augment or control the reactive power that is created by generators. These devices include shunt capacitor banks, synchronous condensers, and static VAR compensators (SVCs). Each of these devices can both create or absorb reactive power, which helps the system maintain an appropriate voltage. Additionally, because they are considerably smaller than your typical power plant, they can be distributed across the transmission and distribution system. This is especially important since reactive power does not travel well over power lines, and so must be controlled near the source of any voltage disturbance (which is typically close to customers).

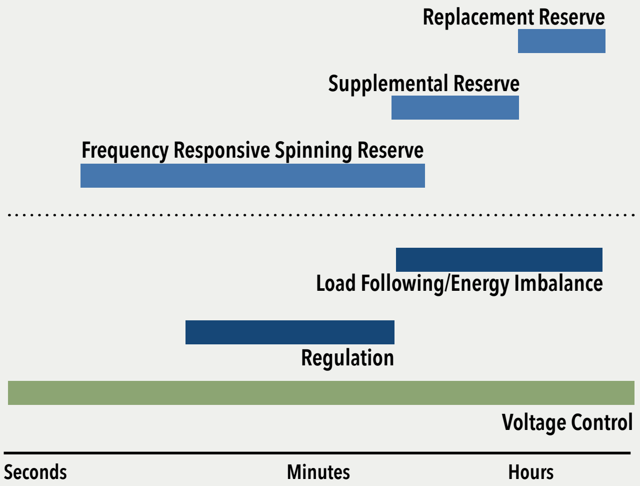
Voltage Support

Voltage support is required to keep the system running smoothly and move power from where it is generated to where it is consumed. The primary objective of voltage support is to maintain grid voltages within a stable and secure range. Reactive power is an essential tool for voltage support and is used to regulate and control different voltage levels across the system. Conventional and renewable generators, as well as other grid devices such as capacitors and synchronous condensers, can provide voltage support with reactive power. For more information on voltage and reactive power, see the sidebar "Measuring Electricity: The Basics" (page 6).

In general, injecting reactive power into the system raises voltages, and absorbing reactive power lowers voltages. At very low levels of system load, voltages may naturally increase because transmission lines inject reactive power into the system when they are carrying little load. At high load levels, however, transmission lines absorb reactive power, causing voltage to drop. To maintain the necessary voltage, grid operators activate generators and other resources to respond to such changes in voltage and adjust output accordingly in order to maintain a constant voltage on the system. Also, since reactive power cannot travel long distances, resources capable of providing voltage support must be distributed across the system in all areas.

These primary tasks—maintaining supply and demand balance, frequency control, and voltage support—all must occur quickly in order to maintain normal grid operations. They occur on slightly different time scales, but all within a matter of minutes. The quickest responses are the automatic responses of running generators that adjust voltage and provide primary frequency response or automatically follow a signal from the system operator. Next is supply and demand balance, achieved through quick adjustments in a matter of minutes, such as the load following resources that can ramp to follow load up and down. In times of unexpected grid hardship (called contingency situations), additional reserve resources are also brought online to restore the load-supply balance and stabilize frequency.

Figure 6. Time continuum of grid support services



Source: FERC (Kirby 2004)

These three tasks require constant coordination and situational awareness among grid operators, power plant owners, and others. In the following section, we will discuss who is responsible for the performance and oversight of these reliability tasks.

Coordinating Reliability

The U.S. electrical grid is actually split into three primary **interconnections**, each one a highly complex machine consisting of all of the interconnected generators, transmission and distribution equipment, and consumers. While all three interconnections operate on a 60 Hz frequency, the frequencies are not synced to one another, and each interconnection is functionally independent of the others. Many different federal, state, local, and private entities work together in each of these interconnections to maintain the balance of supply and demand every second of every day of every year.

National Regulators

At the federal level and encompassing all interconnections, the mission of the North American Electric Reliability Corporation (**NERC**) is to assure the reliability of the **bulk power system** in most of the U.S. and Canada. (The "bulk" system is typically larger transmission lines that are 100 kV and bigger, while smaller, more local "distribution" lines are typically under the jurisdictions of individual states.) To do this, NERC develops and enforces Reliability Standards that govern much of the grid's operation, such as: the frequency required on the grid, including a limit for how much, how often, and how long it can deviate from this level; minimum level of reliability services and resources (for example, the quantity and type of contingency reserves); and operating requirements for those that own or control generation or transmission infrastructure, such as ensuring that voltage levels, reactive flows, and reactive resources are monitored, controlled, and maintained within limits in real time. NERC also conducts detailed annual and seasonal planning processes to assess the performance of the current system and

DID YOU KNOW?

Once NERC develops a standard, it is subject to FERC review and approval before the standard becomes final and enforcable. NERC authorizes Regional Entities to oversee and monitor compliance with its Reliability Standards. Each of these Regional Entities is responsible for ensuring all bulk power system owners, operators, and users within their designated area adhere to these Standards, and may impose penalties or sanctions upon violations of the rules. If an entity is found to have violated the standards, NERC requires that it develop and abide by an appropriate mitigation plan. If issues are left uncorrected or repeated, NERC or a Regional Entity can impose sanctions or recommend to FERC that penalties be imposed.

project changes or updates likely to be necessary in the years ahead. NERC itself doesn't implement its findings and recommendations from these studies; instead, NERC passes them on to regional reliability organizations and grid operators to inform their planning and operations.

NERC is subject to oversight by the Federal Energy Regulatory Commission (**FERC**), an independent agency that regulates the interstate transmission of electricity, natural gas, and oil. FERC has exclusive jurisdiction over the transmission and wholesale sale of electric energy in interstate commerce and over all facilities for such transmission or sale of electric energy, putting it at the center of many markets and investment plans that aim to improve reliability and incorporate renewable energy. (FERC does not have jurisdiction over the interconnection that covers most of Texas, since it is confined wholly within Texas.)

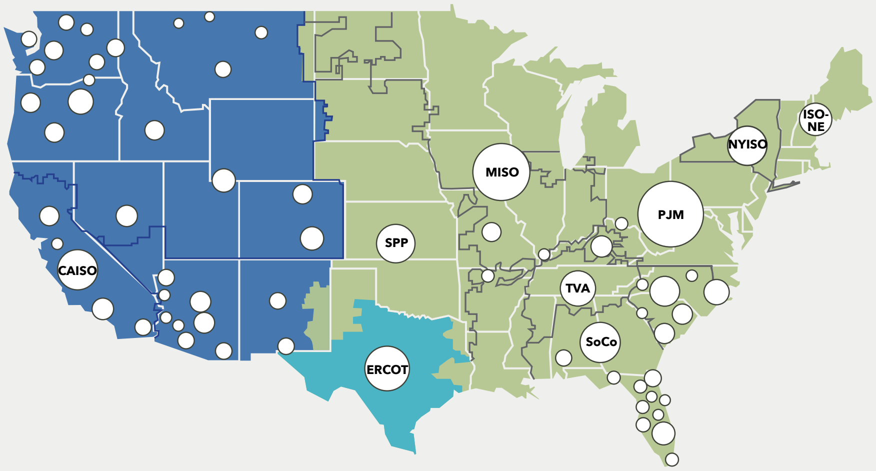
Local and Regional Electrical Authorities

While FERC and NERC are responsible for developing and enforcing reliability standards across the entire system, they don't actually operate the grid and maintain reliability on a day-to-day basis. That's the responsibility of **Balancing Areas** (BAs). There are 74 balancing authorities in North America—one in Texas, 37 in the Western Interconnect, and 36 in the Eastern Interconnect. They vary in size from smaller single utilities to larger regional grid operators. Within an interconnection, transmission lines connect the BAs together to form a single web that is the grid. BAs are responsible both for real-time balancing of load and supply within their boundaries, and for long-term planning—ensuring that there are enough resources and transmission for the system based on forecasts of future demand. Considering that electricity moves throughout each interconnection without much regard for individual BA boundaries, the BAs must also coordinate closely with one another to maintain balance across the entire interconnection.

DID YOU KNOW?

Balancing Areas can serve regions as small as a single town or as large as multiple states: in 2015, the largest had a peak of 136,614 MW, while the smallest had a peak of only 38 MW!

Figure 7. Unites States Balancing Areas



Source: EIA

About two-thirds of electricity deliveries in the U.S. occur in large, multi-utility BAs known as **regional transmission organizations (RTOs)** or **independent system operators (ISOs)**. Very similar in design, these FERC-jurisdictional non-governmental organizations operate regions of the grid and run markets that dispatch generation and demand resources within their regions. Transmission-owning utilities in these regions have transferred operational control of their transmission lines to the RTO or ISO. The ISO/RTO manages the system, ensuring that all parties—including, for example, independently owned power generators and providers of demand response—have fair access to the electric system. The ISO/RTO is in charge of ensuring that no single company or facility is given an unfair advantage in dispatch decisions. Instead, choices are made based on consistent market rules and requirements and dispatch algorithms. Seven ISOs/RTOs currently operate in the U.S.

Apart from their larger size, another attribute unique to ISOs/RTOs is that they operate electricity markets to efficiently dispatch energy across larger regions. These market designs vary by ISO/RTO. All conduct real-time electricity markets that balance supply and demand day and night based on a concept called "security-constrained" economic dispatch and unit commitment. This means that the market selects those generating facilities that produce energy at the lowest operating cost to reliably serve consumers, subject to any operational limits of generation and transmission facilities. Fuel cost, which is a funtion of both generator efficiency and fuel prices, is a primary factor influencing dispatch order. This market structure is intended to minimize cost, meet reliability criteria, and provide a level playing field for different types of generation.

ISOs/RTOs also typically operate markets for products called **ancillary services**. These crucial reliability services, such as system reserves and regulation, help the system operator to fine-tune the system to balance short-term changes and respond to system contingencies. The increase of renewable generation in the system has led to changes to ancillary services markets in some areas to target increased flexibility.

Finally, some ISO/RTOs operate capacity markets, the goal of which is to ensure that a sufficient supply of electricity and demand-side resources is available in the future. As with the other electricity markets, capacity markets are highly structured in design, with the grid operator defining the future capacity requirements, typically focused on a forecast of future summer and winter peak demand. Sellers

DID YOU KNOW?

ISOs/RTOs constantly monitor supply and demand on the grid to ensure that both are in balance. So how does this work? Energy is dispatched in a manner that seeks to provide the least-cost options in meeting demand, driving the market to dispatch resources generating electricity at low costs before those of higher costs. Suppliers looking to sell their power in the market can make offers to sell their power prior to the start of the operating hour. Grid managers will then be able to see all of the available power that was offered into the market. To meet demand on a real-time schedule, the market typically dispatches energy every five minutes. For example, say a system operator is seeking 300 MW of power in the next hour. The system operator–or, more accurately, the operator's computer–will be able to see that the least expensive power available to serve demand–that is, not restricted by transmission lines being full, or other reliability constraints–is, for example, 100 MW of wind power offered at $10, plus 100 MW of solar power offered at $20, and 100 MW of natural gas generation offered at $30. This final price–the cost of the last resource dispatched–sets the "market clearing price," which determines the price that all participating generators receive for their power during this hour.

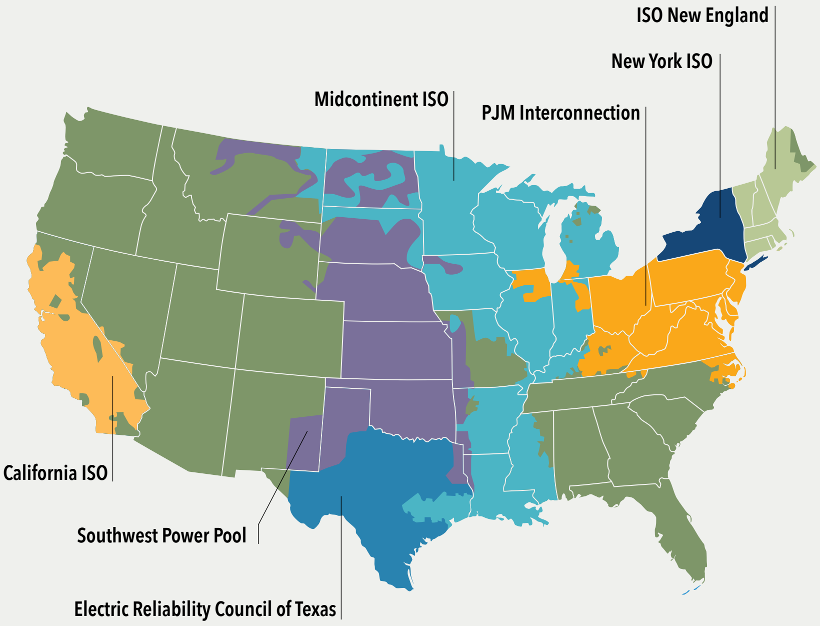
of capacity promise to be available up to three years in the future, even if their energy is not actually necessary at that time because of lower-than-expected demand. These markets act as an insurance policy for the grid, and they also provide additional revenue to important supply resources.

The remaining balancing areas that are not part of an ISO/RTO, primarily in the Southeast and West, control dispatch within their individual areas and coordinate electricity imports and exports with neighboring balancing areas. Examples include the Southern Company in the Southeast and the Bonneville Power Administration in the Northwest. About a third of the electricity delivered in the U.S. is generated in these non-ISO/RTO regions.

DID YOU KNOW?

Long-term resource adequacy is also critical for maintaining reliability. Many states have long-term electricity planning requirements, overseen by the state public utility commissions, that obligate the utilities in their state to submit multi-year plans explaining how they will reliably and cost-effectively serve predicted future demand while meeting all federal, state, and local environmental, energy policy, and other standards. In these states the utilities typically are vertically integrated, meaning that they own a complete system of distribution and transmission lines and power plants. In states that have restructured their electricity industry, utilities generally are not responsible for long-term resource adequacy. In nearly all of these states, RTOs and ISOs use capacity markets to help ensure long-term resource adequacy.

Figure 8. Map of Unites States ISO/RTO Regions



Source: FERC

2. Integrating Renewable Energy into the Electric Grid

Wind and solar energy are becoming increasingly competitive sources of generation because of plummeting capital costs, technology improvements, and the continuation of federal tax credits (see "Renewables Are Hot Right Now" on page 16). As of June 2016, the grid provides support for 75.1 gigawatts (GW) of wind capacity and 15.1 GW of utility scale solar (nameplate capacity), with both likely to continue to grow. Unlike traditional fossil fuel–powered generators, whose largest ongoing costs are the fuel they consume, wind and solar projects rely on freely available resources; their primary expense is the initial capital cost of construction. Once they are running, their ongoing maintenance and operating costs are much lower than nuclear, coal, and gas because they have fewer moving parts to wear down over time and do not face fuel supply and waste disposal issues, such as procuring gas, keeping coal on site, disposing of waste ash, or storing nuclear waste.*

The grid has seen major changes in the generation mix before, as changing economics and policies triggered waves of new nuclear and natural gas resources into the electric system (see "A Half Century of Integrating New Resources" on page 19). Prudent grid planning and operational changes helped to smoothly integrate these new resources into the electric grid. Similarly, grid managers are integrating renewables while taking into account several unique operational characteristics. In this chapter, we highlight key considerations and methods for integrating renewables into a reliable electric grid.

WHY WIND & SOLAR?

For much of this paper, we use the term "renewable energy" to refer to generation from wind and solar facilities. There are many other types of renewable generators, such as those powered by heat from the earth (geothermal power), flowing water (hydroelectric or tidal power) and bioorganic material (such as biogas from decomposing municipal waste or wood and crop waste). In some regions such as the Pacific Northwest and in Maine, hydroelectric power is a majority of the renewable power.

However, the growth in wind and solar generation dwarfs that of any other resource. Technological and production cost advancements have been concentrated in these technologies; these resources are also the focus of tax credits. In 2015, wind and solar accounted for 67 percent of all generation capacity additions. When looking forward, it is reasonable to assume that most new renewable energy will be wind and solar power. At the least, wind and solar generation will constitute most of the short- to mid-term growth in renewable energy.

---

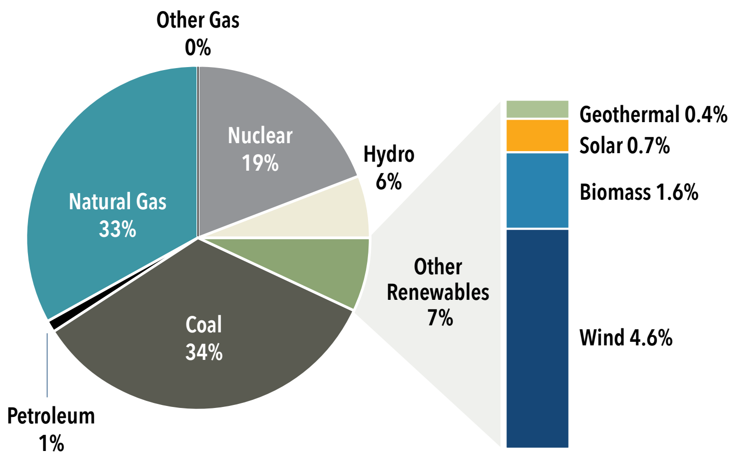
* Geothermal and biomass facilities tend to look more like conventional generators in their maintenance requirements, and biomass requires fuel deliveries akin to those of natural gas (though these facilities are typically sited close to biomass feedstocks with biomass stored on site, somewhat lessening the infrastructure constraints).

RENEWABLES ARE HOT RIGHT NOW

Electricity generation and capacity from renewable generators have grown more in recent years than ever before. Renewable generators, including hydropower, generated over 13 percent of total electricity in the U.S. in 2015 (see Figure 9).[8] Non-hydropower renewable energy generation more than tripled in the past decade, rising from only 2.4 percent total of electricity generation in 2006 to more than 8 percent in 2016—reflecting a 14 percent average annual growth in renewable generation.[9] In 2015, wind and solar accounted for 67 percent of all generation capacity additions.[10] As of October 2016, the grid supports over 108 GW of utility-scale solar, wind, geothermal, and biomass generation—compared with 1,170 GW total generation on the system.[11]

Several factors are driving this rapid growth. A number of states have developed and implemented programs to increase renewable energy. Currently 29 states have developed Renewable Portfolio Standards (RPS), which require a specific percentage of the state's electricity consumption to be supplied by renewable generators. Five of these states are working to achieve an RPS of at least 30 percent by 2020, and 17 states have set targets between 20 and 30 percent to be reached between 2020 and 2026. California's RPS sets especially high targets, requiring the state to obtain 33 percent of its energy needs from renewables by 2020 and 50 percent by 2030. California leads the country in solar installations, adding 3.3 GW of solar capacity in 2015. This brings the state's total solar capacity to 13.9 GW, enough to power 3,494,000 homes.[12]

Figure 9. 2015 total electricity generation



Source: EIA

Another state driving forward high levels of renewables is New York through its August 2016 Clean Energy Standard, which will require the state to procure 50 percent of its electricity supply from renewable resources by 2030. In addition to establishing a 50 percent RPS goal, the state has implemented the NY-SUN Initiative to grow the use of solar power and reduce consumer energy bills. In the first two years of the program, New York added 316 MW of new solar capacity.

Earlier in 2016, Oregon passed a new and ambitious RPS law, requiring the state to reach 50 percent renewables by 2040.

In addition to state-level policies driving the growth of renewable generation, renewable installation costs have fallen dramatically in the past decade due to aggressive scaling, technological advancement, and increasing global production. Improvements include higher wind turbines (that can reach faster winds), more efficient photovoltaic cells, and better inverters that more efficiently translate generation to AC power. These and other improvements contribute to cheaper installation costs and energy prices that in many cases are less than the costs of conventional fossil-fired resources. Residential and utility-scale solar system materials and installation prices have continued to fall as the industry expands and is supported by financial incentives, with the cost of solar installation dropping over 70 percent in the past decade.[13] Similarly, the capital cost of new wind turbines has fallen by over 60 percent since 2009.[14]

Federal tax incentives also continue to contribute to the growth: the Investment Tax Credit (ITC) for solar projects, and the Production Tax Credit (PTC) for wind, biomass, and geothermal generation. These incentives were due to expire in 2017, but in December 2015 Congress extended the ITC and PTC for several more years.

The Increasing Need for Grid Flexibility

While the variability and weather-driven changes in output of renewable resources are not in and of themselves problematic, these characteristics are helping to reveal a potential weakness in the future electric grid: a lack of sufficient flexibility to manage consistently high levels of renewable energy. A future, cleaner grid will need more flexibility and responsiveness to address changing sources and characteristics of generation and demand. These changes will include, for example, rising levels of renewable generation, increased customer-located rooftop solar and other generation, electric cars, "smart" appliance development, and the need for greater grid resiliency and security.

A flexible grid is one that is able to adapt to changing conditions in the system—demand, generation (variable and otherwise), and other factors—nimbly, cost-effectively, and reliably. This flexibility can and will be provided by many sources: distributed resources, conventional natural gas plants, demand response, renewable generators (including both variable wind and solar and baseload resources like geothermal and biomass), and existing and new energy storage. Broader regional coordination makes it possible to access more flexibility from a larger pool of resources. Indeed, part of ensuring a strong grid in the future will be doing a better job of accessing the flexible attributes of existing generating resources, which are largely conventional fossil-fueled, fully utilizing future technologies such as storage, and optimizing additional new variable resources.

A flexible grid is one that is able to adapt to changing conditions in the system—demand, generation (variable and otherwise), and other factors—nimbly, cost-effectively, and reliably. This flexibility can and will be provided by many sources.

The growth of renewable energy is creating the need for additional grid flexibility services in several areas. Two of the most prominent are rapid ramping and overgeneration. Rapid ramping is especially important to integrating large blocks of solar resources. Because solar resources located in close proximity typically start and stop generating at similar times, fast-responding resources are often needed to help with these ramps up and down—scaling back generation in the morning, as solar fills in, and picking up generation in the evening. These ramps can occur more quickly than the cyclical consumer demand changes occurring throughout the day. As we discuss later, renewable and other resources can provide services that assist in managing this ramp. Some regions with high renewable penetrations also have begun to experience **overgeneration**, when there is more renewable generation than needed on the system to serve demand. More flexibility on the system, as discussed later, can help to limit these periods and avoid cutting back, or curtailing, renewable generators.

Variability and Forecasting

The two fastest-growing sources of renewable energy today are wind and solar power. Their output is uncertain and variable in that it is weather-dependent rather than controlled exclusively by the facility operator. The uncertainty of these resources derives primarily from the possibility of forecast error—because weather doesn't behave precisely as predicted, forecasted output is not entirely certain. Additionally, these resources are variable in that weather, even when forecasted well, is inherently changing, with wind speeds and clouds affecting second-by-second output.

Crucial to managing the variability of these renewable generators is being able to "see" what the available fleet of renewable generators is currently capable of producing and forecast what they can produce in the coming minutes and hours. This creates a more accurate picture of grid conditions and the likely output of renewable generators throughout the day. Significant progress has been made on this front. **Telemetry**, two-way communication between renewable generators and grid managers, can provide consistent data on wind speed or sunshine, power output, site temperature and humidity, and other operating factors. These data create a short-term picture of power from the wind and solar plants, which allows grid managers some lead time to plan for changes in operations. For example, if telemetry and forecasts indicate that wind speed is increasing, a grid manager can plan to decrease generation in another area in order to prepare for higher wind output.

In the longer term, over the course of days, wind and solar power forecasts based on advanced weather forecast models also help to integrate renewable energy. Many different methods are used to forecast solar irradiance (the amount of solar energy reaching the earth) and wind speed. The broadest are climatological models, which look at long-term expected values that will affect resources—these are the models that can tell you that a region is likely to have more sunny days than cloudy ones and thus has a good profile for solar generation. Advanced weather prediction models provide more accurate insight, using tools similar to those used by your meteorologist to predict the next week's temperature, wind, humidity, and solar irradiation, and monitoring weather fronts moving through a region, all of which affect the operations of renewable generators.

For a more detailed look that is especially relevant for solar forecasting, satellite images can predict future cloud locations up to five hours ahead in some areas. Sky imagers—cameras that take pictures of the sky from the ground—can give more detail on cloud cover (thickness, speed and direction of movement) but are typically accurate only for a thirty-minute window. Several of these models are used simultaneously, and their data are dynamically incorporated into statistical "learning" models that help to balance the uncertainty from each method and combine forecasts from many different sources. With these models, grid operators and generators can get a better sense of possible conditions in the coming days or hours and plan accordingly.

Distributed Energy Resources

Forecasting and telemetry are especially important for **distributed energy resources**—smaller generators that are located closer to where electricity is used, or "distributed" among homes, businesses, and industries. Because wind and solar generators are not dependent on deliveries of coal or natural gas and do not create local pollution concerns, they can be dispersed over rooftops, backyards, and other areas that have not traditionally had generation. This locational dispersion can help mitigate forecasting errors through the law of averages—weather events that change output in one area may not affect generators in another, helping to smooth total regional generation.

However, many small generators find it cost prohibitive to have sophisticated communication equipment, limiting visibility of these resources to grid operators. Additionally, because rooftop solar and other customer-sited resources historically constituted only a small portion of generation, grid managers did not require them to have communication. As the number of these resources continues to grow and increasingly affect grid operations, grid operators in some areas are developing aggregated telemetry units that can combine data from multiple units at lower cost and improve information from distributed generation. Planning for installations can also help appropriately site some distributed generation to provide reliability services, such as local energy and reactive power, that can limit the need for transmission and distribution lines.

A HALF CENTURY OF INTEGRATING NEW RESOURCES

The influx of renewable generation is the latest in a half-century-long line of dramatic changes and shifts of technology in the electric grid. From nuclear to natural gas generators to transmission expansion, the system has incorporated these technological changes, emerging each time more robust, reliable, and flexible.

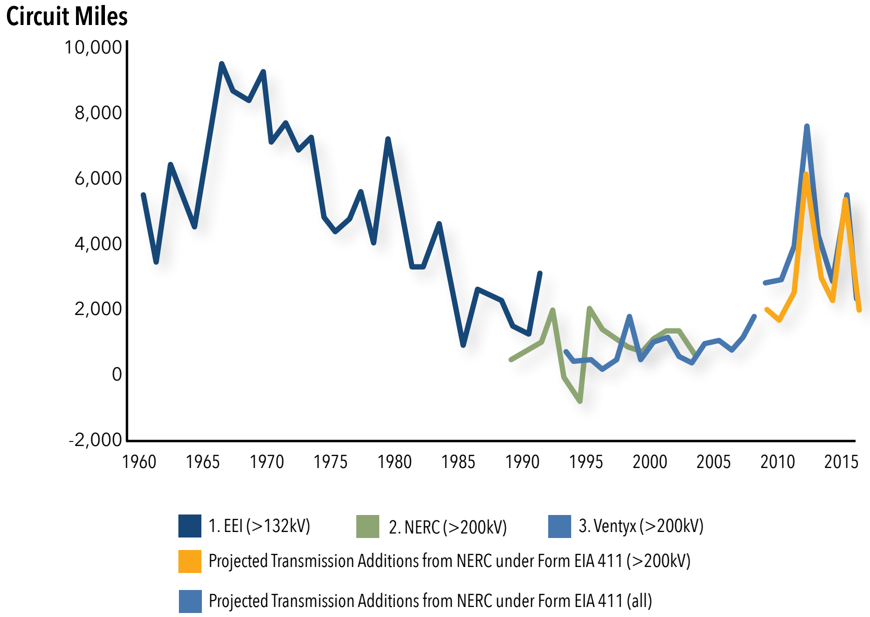
The first major shift was to add nuclear power to what was then a predominantly coal-heavy generation fleet. In the roughly two decades from December 2, 1957 (when the Shippingport nuclear plant near Pittsburgh went on line), and April 7, 1977 (when President Carter halted plans for reprocessing spent nuclear fuel), the U.S. added roughly 46.2 GW of nuclear.[15] Though nuclear additions continued through the 1980s, few plants have been built since. As of 2015, nuclear power constitutes about 20 percent of the country's total generating capacity, which is very close to nuclear power's share in the late 1980s.

The next main generation shift occurred in the 17 years between the acceleration of competitive wholesale electric markets (prompted by the passage of the 1992 Energy Policy Act) and the end of 2008, when the economy ran into a deep recession. During this period natural gas overtook coal as the dominant fuel for generation capacity additions.

Grid operators successfully integrated these two large waves of new generation capacity additions into the grid without disruption to the reliability of the system, even though they had different operating characteristics from the dominant coal generation. For example, nuclear power is extremely difficult to ramp up and down to match daily demand patterns because the predominant U.S. plant is designed to operate at constant power output levels. The large size of nuclear power plants (1,000 MW or more per generating unit in many cases) means that the grid managers have to plan for sufficient replacement generation to be held in reserve in case a unit or plant trips off line. Natural gas required an entirely new infrastructure for shipping, distributing, and storing gaseous fuel, which could no longer be shoveled into train coal cars or piled alongside a power plant.

Over the course of these cycles in resource expansion, the transmission system mirrored these changes to some extent. During the period between the mid-1960s through early 1980s the country saw great expansion of the transmission system to support a large build-out of new resources in response to reliability concerns. In part, this build-out strengthened connections among previously isolated grid areas, allowing regions to share reserves and support one another's reliability. Following this period, transmission development declined somewhat. Looking ahead, NERC predicts a spike in transmission expansion to replace aging infrastructure, incorporate new technologies, and support increasing renewable energy deployment.

Figure 10. Historic and projected expansion of transmission circuit miles



Source: DOE

Transmission and Distribution Planning

A robust and stable electric delivery system of transmission and distribution wires and equipment is also key to successfully integrating higher levels of renewable generators. As the mix of energy resources shifts in the coming years, our transmission and distribution framework will need to adapt to include disbursed, distributed energy resources in addition to larger power plants. Additionally, new central station wind and solar plants—large generators typically built by or contracted to utilities—may not be sited near grid locations with excess power carrying capacity, and lines may need upgrading, or new lines will need to be built.

The current **transmission system** is restricting further wind and solar deployment in states with high penetrations of renewables, like Texas and Hawaii. Adequate transmission expansion can help to support greater renewables deployment while supporting reliability. A strong transmission system can also allow renewable generators to balance one another across larger areas. For example, when solar panels in Arizona are generating more power than is demanded during a sunny afternoon, transmission lines could transport this electricity to meet demand in Wyoming when wind generation is low.

DID YOU KNOW?

The Southwest Power Pool's 2016 report "The Value of Transmission" highlights the importance of transmission modernization in planning for higher renewables. In 2007, the transmission operator's territory–covering 14 states–supported renewable generation making up 5.6 percent of total generation resources. After significant transmission upgrades and expansion, by the end of 2015 SPP was able to smoothly integrate more renewable generators, growing to over 15 percent of total generation for the service territory.

Regional Dispersion and Coordination

Regional dispersion of energy resources matters too. In the same way that resource adequacy is most efficiently addressed through regional management, large-scale coordination can smooth out renewable generation variability to reduce the system balancing needs. ISO/RTO markets can enhance the integration of renewables across wide regions by balancing generation and load across large regions on very fast intervals. In this way, a wind generator that increases output at one corner of the grid can be used to serve an increase in load at another corner. Additionally, because these markets run every five minutes, they can respond quickly and follow the variability of load, wind generation, and solar generation more easily than a system using hourly schedules. Furthermore, a broad coordinating footprint takes advantage of the reduction in variability from combining a geographically diverse set of renewables *and* making better use of a larger set of flexible resources that can respond to any remaining variability.

Regional coordination takes advantage of the reduction in variability from combining a geographically diverse set of renewables and making better use of a larger set of flexible resources that can respond to any remaining variability.

In nonmarket regions like the inter-mountain West, this coordination can occur through "energy imbalance" markets (or EIMs), which provide real-time balancing activity for the purposes of increasing efficiency of regional changes in supply and demand. In the words of the National Renewable Energy Laboratory (NREL), the "EIM is intended to provide better generation-load balancing by being both big and fast."[16] An example of an EIM is currently in place in the West, which is the largest area without traditional organized markets, and it has shown positive results—see "Western Energy Imbalance Market" on page 21 for more details.

Energy Storage and Demand Response

Some areas are also beginning to use **energy storage** to support grid reliability. The largest existing form of energy storage is pumped hydroelectric storage. Most of the grid's 22,000 MW of pumped hydro has been in operation for a generation or more and is used to balance large inflexible baseload coal and nuclear plants. It does not typically have the operational flexibility to help integrate renewable resources. However, newer advanced grid-level storage is seeing rapid growth. At the end of 2015, U.S. storage capacity from batteries and other advanced technologies reached 221 MW, up 243 percent from 2014, and this is expected to surpass

4 GW by 2020.[17] PJM alone has 1,831 MW of new storage under study in the interconnection queue, and California has an energy storage procurement target of 1,325 MW by 2020.[18] Most added capacity will likely be at the utility scale; however, residential storage also will add to the growing capacity nationwide. Electric vehicles can perform the role of both storage and demand response, especially when connected at centralized charging stations.

Though nascent in their development, advanced storage technologies can store energy through various mechanisms when it is not needed to serve demand and deliver this energy to the grid when demand rises (see "Storage as a Grid Reliability Tool" on page 22). If the economics for the technologies improve, storage could serve peak load by feeding the grid with existing power rather than bringing new generation online. Storage also could help to maintain reliability by reducing grid congestion and providing reserves and reliability services. Demand response, as discussed earlier, can provide a very similar service, especially during peak times. As with all resources, storage and demand response can be viewed as components that, in combination with conventional and renewable resources on the grid, can be economically balanced to support grid reliability.

WESTERN ENERGY IMBALANCE MARKET

The Western Energy Imbalance Market (EIM) was formed in November 2014 in order to help balance the real-time supply and demand in parts of the Western Interconnection by coordinating among multiple balancing authorities. California ISO (CAISO) utilities and the PacifiCorp system in parts of seven states were the initial participants. NV Energy, Arizona Public Service, and Puget Sound Energy subsequently joined the EIM, and another three entities have planned entry between 2017 and 2019. The Western EIM's advanced market systems automatically find the lowest-cost energy to serve real-time consumer demand across a wide geographic area. Establishing this market has opened up opportunities for the region to benefit from a larger geographic pool in which to dispatch energy.

The benefits of the Western EIM include reducing reserve requirements 30–46 percent, depending on the type of reserve. These benefits would further increase with a larger EIM since more generation would be available to be utilized and distributed to where it is needed. Enhanced real-time market operations also enable generation to be used more effectively, avoiding unnecessary system losses or curtailment. Variability from renewable generation is muted since peaks and lulls in production can be balanced by working to optimize resource potential and energy availability in the market.[19]

The Western EIM has proven to be cost-effective as well. The cost benefits include lowering the total cost of generation (by allowing the most cost-effective resources to generate) and limiting the use of expensive generation-demand balancing services. Since expansion of the CAISO in November 2014, the EIM has produced benefits of more than $114 million. This includes avoiding curtailment of more than 335 GWh of wind and solar power, which in turn avoided over 143,000 tons of CO_2 emissions.

To fully take advantage of interregional planning, these same states are considering creating a larger ISO/RTO, based in CAISO but spread throughout the region. This sort of broader market would help to integrate renewables in several different ways, such as responding to an afternoon of low solar generation in California by supplementing with solar power from Nevada, or wind generation from Wyoming. This is important, because it means that renewable generators can to a certain degree back each other up, thereby reducing the need to for fast-ramping gas generator storage and demand response to fill the variability swings in wind and solar output.

Inverters and Converters

Nearly all of our nation's grid, and our home appliances, operate on alternating current (AC) electricity at 60 hertz. However, some renewable energy power systems generate **direct current (DC)** electricity. Photovoltaic solar panels and battery storage, for example, generate DC electricity, and they require an **inverter** unit to transform the current into AC power before injecting into the grid. In contrast, generators with spinning turbines—wind, gas, coal, etc.—produce AC electricity. Even though most wind turbines produce AC, they use **converters** to convert this variable-frequency current to the stable 60 hertz frequency of the power grid.

STORAGE AS A GRID RELIABILITY TOOL

A number of types of storage technologies have been developed for a variety of applications. Though storage is often mentioned in the context of renewable integration, it has many other applications as a grid reliability tool.

BATTERIES can be applied at various scales to store excess energy generated by renewable sources. Batteries have the ability to be sited nearly anywhere on the grid, providing utilities and customers an opportunity to better manage their energy. Lithium-ion batteries are the most widely used in grid application, making up 96 percent of total storage deployment in 2015.[20] Future electric vehicle integration is largely supported by the advancements and scale of lithium-ion batteries.

THERMAL STORAGE captures the power of the sun when it is available, storing heat in molten salt, water, or other fluids for later use. Concentrating solar power (CSP) is the main application of this technology today. There are various types of CSP, but most have a number of large mirrors that focus the sun and transfer captured heat to tubes of liquid—reaching temperatures up to around 750 degrees Fahrenheit. The heat is used to generate steam to spin a turbine and generate electricity, or it is stored for use at a later time. The fluids used in these systems are recycled through the system once they are cooled, creating a self-sustaining generation and storage system. The 110 MW Crescent Dunes CSP project came online in 2015 and includes ten hours of full power storage capacity.

FLYWHEELS rely on the concept of inertia, using a motor to store kinetic energy in a device that spins at very high speed. When power is needed, the grid can pull energy from the flywheel, using the motor as a generator to return the energy to the power grid. Flywheels offer strong and rapid frequency response services by providing fast response and high ramp speed.

PUMPED HYDROPOWER harnesses the power of gravity to provide energy storage. In this application, water is pumped from a source at low elevation to a reservoir at a higher elevation using low-cost electricity during the night or other periods of low energy demand. Then, at times of peak demand, the water is released and is sent through turbines, causing them to spin and generate electricity. Pumped hydro supports grid reliability by contributing to system frequency control and reserves. It is the most widely used form of storage in the U.S. today, providing nearly 22,000 MW of total storage capacity in 2014. However, permitting rules and the lack of suitable geographic locations may limit expansion of pumped hydro in the future.

COMPRESSED AIR ENERGY STORAGE, similar to pumped hydro, uses low-cost electricity during times of low demand to compress air under high pressure and pump it underground. When electricity is needed at times of peak demand, this compressed air is used to produce electricity with a gas turbine (often in conjunction with natural gas, but made much more efficient by the use of the compressed air). There is currently only one compressed air energy storage installation (110 MW) in operation in the U.S.

These inverters can also play a helpful role in ensuring grid reliability and stability, particularly with higher renewable penetration levels. They can quickly act in response to real-time grid conditions, reacting to the ebb and flow of power supply. Because they use computer-like controllers to electronically couple with the power grid, they can be programmed to provide many useful features. Historically, when the grid experiences a disturbance, some distributed solar inverters have been programmed to sense this imbalance and shut off. Some states and key regulatory bodies have begun to work with local electric utilities and inverter providers to change inverter controls and standards to improve inverter performance, ride through disturbances, and provide additional grid support. Utility-scale wind and solar plants already have many of these advanced features, though their utilization in most grid areas is low.

Planning for Growth

Renewable energy is a growing source of electricity. Many areas are already planning for renewable electricity levels as high as 50 percent of annual electric supply. Ten states have policies targeting between 25 and 40 percent renewable deliveries within a decade.* California and Oregon have 50 percent renewable energy standard targets set in law, with New York following suit with its recently finalized Clean Energy Standard aiming for 50 percent renewables by 2030. Vermont will require 75 percent of all electricity delivered to customers to come from renewable resources by 2032. Other regions and researchers have conducted studies that show that even higher levels are feasible (see "How Much Renewable Electricity Is Possible?" on page 24).

DID YOU KNOW?

Inverters are regulated by the Institute of Electrical and Electronics Engineers (IEEE), which establishes protocols relating to performance, operation, testing, safety, and maintenance for the interconnection of distributed energy sources into the electric system. Inverters for distributed resources, specifically, are regulated under Standard 1547, which regulates activity of distributed energy resources in response to disruptions in grid power supply, requiring them to cut connection to the grid—to drop or "trip" offline—at specific high or low voltage thresholds in an effort to maintain safe conditions for users of electricity, other generators, and utility workers. However, an unintentional consequence of this standard is that in periods of grid stress, the mass tripping of distributed generation can exacerbate voltage and frequency disturbances.

To address this issue and others, in 2015, an amendment was added to the standard which gives the distributed energy resource new authority: to adjust active and reactive power; stay online, or "ride through," periods of voltage variations; and work with the grid operator to decide how to respond to frequency abnormalities. The standard is currently under a full revision process, to be completed by 2018. The revision will address the needs and functions of an evolving grid by providing greater flexibility required for higher distributed renewable penetration, as well as allowing for the integration of smart inverters and the expansion of communication between inverters and grid operators. NREL reports that the revision will be designed to allow distributed energy penetration levels to meet or exceed 100 percent of peak load.

---

* These states are: Colorado, Connecticut, Delaware, Illinois, Maine, Minnesota, New Hampshire, New Jersey, Nevada, and Ohio.

HOW MUCH RENEWABLE ELECTRICITY IS POSSIBLE?

The U.S. is rich in renewable energy resources, so much so that the country's "technical potential" far exceeds its total energy needs. As more renewables enter the system, grid managers, states, and research institutions across the country are conducting studies to see just how much renewable electricity can be reliably integrated into our grid.

The renewable resources of wind, solar, flowing water, biomass, and geothermal energy are not dispersed evenly across the country. For example, the middle of the country—from Montana and North Dakota in the north, through Texas in the south—has the highest wind capacity potential, due to weather patterns and landscape that allow the highest wind speeds, and therefore the greatest potential for energy generation. Similarly, solar power thrives in the Southwest region of the country, where conditions provide many clear days of strong sunshine throughout the year. In the Northwest, hydropower is in abundance, thanks to its mountainous topography and its precipitation, which lends runoff to reservoirs, streams, and rivers, providing 70 to 80 percent of the region's electricity needs from hydropower.

Hypothetically, assuming full utilization of all renewable resources, NREL estimates that these naturally occurring energy sources could power over 200,000 GW of generation across the country (that's compared with only 1,170 GW of all generating capacity installed today). Using these resources, the U.S. could generate 481,800,000 GWh of energy; in comparison, 2014 total U.S. electric use was only 3,903,000 GWh, less than 1 percent of NREL's estimated renewable technical potential. (Table 1 summarizes the findings of the study, showing the generation and capacity potential of each resource.) However, the NREL study focuses strictly on technical potential, defined by resource availability, transmission system constraints, and geographic and land-use limitations, but does not take into account economic, market, or political feasibility.[21]

Table 1. Total estimated generation and capacity potential by resource

		Annual Generation Potential (thousand GWh)	Capacity Potential (GW)
TECHNOLOGY	Urban utility-scale PV	2,200	1,200
	Rural utility-scale PV	280,600	153,000
	Rooftop PV	800	664
	Concentrating solar power	116,100	38,000
	Onshore wind power	32,700	11,000
	Offshore wind power	17,000	4,200
	Biopower	500	62
	Hydrothermal power systems	300	38
	Enhanced geothermal systems	31,300	4,000
	Hydropower	300	60

Source: NREL

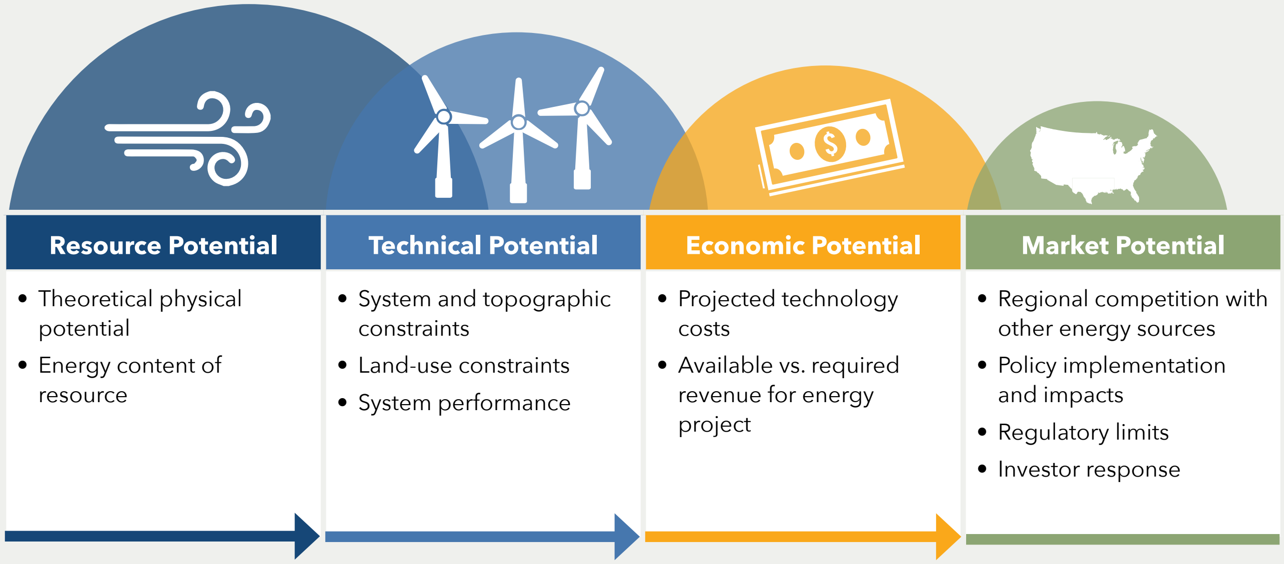
To evaluate more realistic near-term potential, numerous grid managers, states, and research institutions have conducted studies to determine the economic and operational impacts of much higher levels of wind and solar energy—and to identify any changes to operations and markets necessary to economically and reliably integrate such levels.

For example, NREL's 2015 study of the economic potential for renewables in the U.S. found a range of up to 42,000,000 GWh of renewable generation to be achievable—eighty times the installed generation in 2013.[22] In the Southwest Power Pool's 2016 Wind Integration Study, the RTO reported that with certain operational upgrades, it would be possible to reliably operate the system with 60 percent wind penetration. These upgrades include new transmission, transmission upgrades, and technological improvements to better respond and react to voltage variations.

Several regions are already reaching high levels of wind generation. At the end of 2015, Texas led the country with 17,713 MW of installed wind capacity, having experienced record wind levels reaching 12,238 MW in October.[23] These records are consistently broken every year, with daily penetration levels exceeding 45 percent. When considered together, MISO, ERCOT, and SPP had over 30,000 MW of wind on their systems on February 19, 2016.[24]

California currently has the highest number of solar installations, with over 500,000 rooftop solar installations and over 100 utility-scale projects. With more than 12 GW of installed power in 2014, the state was the first to achieve 5 percent of utility-scale generation with solar power. A 2014 study evaluating the potential for California to adopt an RPS of 50 percent by 2030 found that this would be feasible with the appropriate transmission upgrades and improved equipment.[25]

Together, these studies suggest that with continuing improvements in electric system equipment and operations, the U.S. grid will be able to meet the majority of its electricity demand with energy from renewables.



Resource Potential	Technical Potential	Economic Potential	Market Potential
• Theoretical physical potential • Energy content of resource	• System and topographic constraints • Land-use constraints • System performance	• Projected technology costs • Available vs. required revenue for energy project	• Regional competition with other energy sources • Policy implementation and impacts • Regulatory limits • Investor response

Source: NREL

As we continue to integrate renewable energy in higher amounts, grid planners will need to continue to recognize the unique performance characteristics of renewables, including their variability and weather-driven uncertainty. Grid planners can draw on their planning, markets, and operations tools to continue to increase grid flexibility, using resources ranging from natural gas generators to storage to distributed energy resources in order to support renewable integration. Existing tools such as telemetry and forecasting can help plan for and integrate these resources into the grid, and technological improvements in system design can increase renewables' value and ease their integration. Increasingly, renewable generators themselves can support reliability, so that instead of renewables always leaning on the grid for support, the grid can also lean on renewables.

Increasingly, renewable generators themselves can support reliability, so that instead of renewables always leaning on the grid for support, the grid can also lean on renewables.

3. How Renewable Energy Contributes to a Reliable Electric System

Renewable energy can provide value throughout reliability planning and operations. Modern wind and solar technologies can provide **reliability services** from frequency control to reactive power—in some cases more flexibly and quickly than conventional generation. Moreover, renewable power can benefit the grid through increasing the flexibility, locational dispersion, and fuel diversity of the system.

Renewables' Reliability Service Value

While renewable generators can complicate grid management due to their variability, the electric system has proved itself capable of integrating even less flexible, older renewable generation. Now, advanced forecasting and telemetry are helping grid operators manage new and existing renewables, allowing for longer planning times and more tools to account and prepare for variability.

Increasingly, renewables are also able to provide reliability services themselves, sometimes with better performance than conventional resources. From contributing to reserve margins to providing select ramping and regulation services to helping to manage grid frequency and voltage, renewable generators can be actively involved in shaping a clean, reliable electric system.

Ultimately, as renewable penetration levels increase, utilities, grid managers, and regulators will need to ensure that grid systems have the resources to provide essential reliability services necessary to keep the grid functioning. This will include cleaner and more flexible generators such as natural gas–fired units, demand response, and potentially storage to provide the full suite of reliability services. Renewable resources will also be an important part of the mix.

Capacity Requirements

Renewable energy already counts toward capacity requirements (including reserve margins) in grid areas around the country. However, due to the variability of many of these resources, not every megawatt of an installed wind or solar power plant is counted toward capacity requirements. This is also true of conventional generation: since all megawatts of a generator may not be available at all times (perhaps because of an outage, maintenance, or transmission constraints), the amount of capacity that counts for resource adequacy purposes is less than 100 percent. For example, a 100 MW natural gas plant may only contribute 75 MW toward resource adequacy—this is the facility's **capacity value**.

The capacity value of renewable generators is based on these same factors (for example, transmission outages, constraints, and maintenance), plus the additional consideration of how often the generation from the facility overlaps with times of critical electricity demand. This has to do with how much the facility runs as a percentage of all hours in a year—its **capacity factor**—as well as when those hours are. Hours during times when generation is most needed, such as during the day, tend to be more valuable.

Taking into account these operational factors, the more a renewable generator's energy can be counted on to serve more consumers during critical hours when power is most needed, the higher its capacity value. Additionally, capacity values are based on the amount of other generation that can provide capacity at any given time—if there are more resources than are needed to serve demand (such as wind generators at night), the capacity value of each individual generator may be decreased. Capacity values are highly regional and vary by season, with wind values in ISO/RTOs ranging from around 10 to 35 percent, and solar values from 30 to 65 percent in the summer (but sometimes approaching zero in the winter). Because the output of geothermal and biogas plants is not driven by daily weather patterns, their capacity values are determined by the same maintenance and outage factors influencing traditional generators.

Technology advances have continued to increase capacity values for wind and solar resources, primarily by increasing their capacity factor: these resources are more efficient at converting wind and sun into electricity, and, for wind, taller towers access higher wind speeds. For example, PJM has projected that utilizing new renewable technology could increase large-scale solar capacity values to up to 60 percent and onshore wind to around 25 percent as a system average.[26]

DID YOU KNOW?

A generator's capacity factor measures how much electricity the unit produces compared with its maximum total output (often called nameplate capacity). A capacity factor of 100 percent would mean that a generator runs at full capacity (i.e., generating the most possible electricity based on its size) every minute of every day. A 50 percent capacity factor could mean that a unit runs at full capacity half of the time, or at half capacity all of the time (or at 75 percent capacity two-thirds of the time…and many more combinations!).

A unit's capacity value is determined by a planning authority, and it measures what percentage of the total generator output can be counted on to contribute to serving load when needed. This value is partially a function of capacity factor–how much the generator will run, on average, over the course of the year–as well as the specific timing of that generation. Generation that is likely to occur during peak load times (such as in the middle of the day) is more valuable that generation in the middle of the night. Additionally, some calculations of capacity value take into account other resources–if a large block of resources are all projected to generate at the exact same time (such as a large block of solar that will all generate during the day), this can decrease their capacity value.

Like all other forms of generation, renewable energy depends on other generators to make up the balance of the power on the system. The value of a large, interconnected grid becomes clear for renewable energy because the availability of power sharing across the system significantly reduces the need for "backup" generation. While renewables have operating constraints that differ somewhat from those of gas and coal generators, in an interconnected system, every megawatt of potential renewable output does not need an additional megawatt of gas- or coal-fired power waiting and ready to fill in as changes in weather and time of day alter output from renewable generators.

On the contrary, especially at moderate penetration levels and across broader regional areas, little or no additional system-wide reserves are required to integrate renewables. Grid regions have shown this in practice and in preparation for increasing renewable levels:

- MISO needed almost no additional fast-acting power reserves to back up 10,000-plus MW of wind power on the system.[27]

- ERCOT needs only about 50 MW on average of fast-acting stand-by reserves to reliably integrate 10,000 MW of wind into the grid.[28]

- PJM found that a 30 percent regional variable renewable penetration level—adding over 100,000 MW of renewable power—requires no additions in operating reserves, and only 1,500 MW (or 1.5 percent of renewable capacity) of quick-ramping regulation generators such as flexible natural gas generation.[29]

With these minimal additional reserve margins, the low price offers of renewables displace other, higher-cost fossil resources and will produce lower energy market prices while likely resulting in only minimal increases in other electricity costs. Low natural gas prices also reduce energy market revenues for all generators in many regions. One challenge will be how the few fossil-fueled resources that are still required to balance the system will be able to receive sufficient revenues to continue operating.

Large geographic size also helps to improve the collective capacity value of renewable generators (and reduces the need for other balancing services). Changes to wind speed and solar radiation drive output at any given location. However, these factors may be isolated to only one area. Distributing generators within a wide footprint can lower aggregate variability and uncertainty because such changes only affect a portion of total generators within this broad region. As resources in one area produce less power (for example, while clouds roll through), resources in other areas may continue at normal levels. This is particularly true as multiple states and regions work together cooperatively or as balancing areas are consolidated into larger footprints, as has happened in Texas and the Midwest. Some recent examples show:

- In PJM, with 30 percent renewable penetration level, the large footprint of the balancing area "greatly reduced" the impacts of short-term variability in wind and solar generation.[30]

- Because wind patterns in Wyoming and California follow very different patterns, as California wind drops off in the morning, Wyoming wind may be there to pick up the slack.[31]

- A system can reduce the solar variation of 25 generators by 93 percent by simply distributing those generators over 150 miles square rather than siting them in a single location.[32]

As the transmission system continues to develop and strengthen, these sorts of regional balancing partnerships can play a pivotal role in integrating renewables and enhancing system reliability.

Frequency Control

Renewable generators also can provide frequency control. Many new wind and solar facilities have components called "active power controls," which allow their output to be increased or decreased to help maintain reliability. These controls allow renewable generators to provide primary frequency response that is similar to that of the automatic governors on conventional power plants. Using these components, they can quickly and automatically adjust their output to help stabilize grid frequency.

Over-frequency events are addressed through immediate reductions in generation. (Over-frequency is caused when there is too much generation on the system compared with total electricity demand.) Active power control can be used to quickly and briefly reduce generation from wind turbines and solar arrays to return electricity generation back into balance with demand and stabilize frequency. The blade angles in wind turbines can be adjusted so that they catch slightly less wind, which generates less power for a few seconds. Newer solar power plants have smart inverters that can quickly adjust the amount of the available solar power that they then inject into the power grid.

The response to under-frequency events may look a little different. Typically, to be able to respond to these events by increasing output, a generator would have to be running at a level below full potential. In the case of wind and solar power, this intentional operation at levels below full potential output is often called **curtailment**. Such operation is possible but is typically not ideal from an economic perspective, since any (free) wind or sun potential that is not used is wasted electricity generation. However, there may be periods of high grid stress when intentional curtailment is necessary to provide fast response from wind and solar plants to respond to under-frequency events.

Many new wind turbines also have the capability to respond to under-frequency events through an automatic control that temporarily increases the power output of the turbine *above* the facility's current output. For example, if a single turbine has an installed capacity value of 1.5 MW, this feature can allow it to temporarily generate at 1.6 MW for several seconds. This feature works by drawing on kinetic energy—the energy of motion—stored in the spinning rotor of the turbine. Conventional generators tend to contribute this stored kinetic energy automatically in response to under-frequency events, drawing on the natural inertia that is in their rotors spinning in sync with the grid. With these new controls, wind generators are able to enhance this "inertial" response to under-frequency events.

Since solar facilities do not have rotating masses, they are not able to provide inertial response in this way. However, they can inject additional power very quickly if they are currently being curtailed and have additional energy available to provide to the power grid.

DID YOU KNOW?

Most modern wind generators are better than conventional power plants at riding through frequency and voltage disturbances. Since 2005, wind generators have had to meet specific FERC standards in FERC Order 661A that lay out stricter requirements for wind frequency and voltage ride-through than are applied to conventional power plants. Wind generators achieve this through sophisticated power electronics that are able to isolate the wind turbine from the grid, allowing the turbine to remain online during periods of frequency deviation when a conventional power plant may have tripped offline. These same electronics can help both wind and solar plants stabilize the grid following a disturbance, in some cases more quickly than conventional resources.

Balancing Supply and Demand

In the minutes-to-hours time frame, wind and solar facilities can provide load following services that help maintain a balance between generation and demand. To do this, active power controls on solar and wind facilities allow the operator or grid manager to shape the facility output in a variety of ways beyond frequency control. For example, these technologies can respond to automatic generation control signals every few seconds to rapidly increase or decrease output to help balance the system. They can also follow detailed, five-minute schedules that are shared with the central grid operator ahead of time, meaning that the dispatcher can count on a certain level of output on a short-term basis. To allow for increased output in both of these applications, the renewable generators must be initially scheduled below their maximum power output.

If necessary due to limited power system flexibility in a region (or on a small island power system), "ramp rate" controls can limit the rate of increase in power output of a wind or solar power plant, which can minimize any impacts of an otherwise sudden influx of generation. Instead of generators immediately ramping up to full output as sun or wind resources become available, ramp rate controls modulate their increase in output.

Another option to better match generation with demand is to site wind and solar plants so that their typical output level more closely aligns with the rising and falling of daily demand. For example, the Northeast utility National Grid is building large-scale solar installations that are facing southwest rather than south. Traditionally, solar panels face south to maximize total solar irradiation received by the panels over the day. However, by facing southwest, the panels receive less total energy but deliver more of their energy in the late afternoon, which is when National Grid consumer demand picks up as people arrive home from work. Similarly, some solar panels are able to rotate based on operator or automatic instruction, which can provide a comparable service.

Voltage Control and Reactive Power Production

Renewable generators are also able to contribute voltage control and reactive power supply, which are closely linked services.

For example, advanced wind controllers can manage the output from multiple individual wind turbines simultaneously, ensuring that an entire wind power plant maintains the correct voltage at the point of the plant's interconnection to the larger grid. This system can also respond to signals from the larger grid and help support dips or rises in voltage by adjusting unit operations. By minimizing any impact of voltage fluctuations for each turbine and quickly responding to voltage changes on the grid, this "fast and precise voltage control effectively strengthens the grid." Inverter-based wind and solar can outperform typical generators that cannot respond as quickly or accurately, ultimately "*improving* [emphasis added] the overall power system's resilience to large [voltage] disruptions."[33] Some companies are now developing controllers that not only coordinate *within* wind farms, but can also balance voltage contributions *among* farms that are located in the same region.

Rooftop solar arrays and large solar power plants can also help control voltage by adding or absorbing reactive power. Advanced inverters on these resources to sync with the grid can provide dynamic reactive power control. These inverters respond automatically to voltage issues on the grid by either pulling reactive power from the system or creating additional reactive power. In fact, advanced inverters can provide this service even when the generators with which they are coupled are not producing real power—so solar facilities can control voltage in the dead of night and wind facilities can control voltage when the wind is calm. Also, remember that reactive power and voltage control are quite location-sensitive, requiring that these services be provided throughout the grid. Because renewable generators,

DID YOU KNOW?

Most turbines are part of large wind "farms," in which tens or even hundreds of individual wind turbines are maintained and operated by one operator. A wind plant controller can coordinate the turbines to adjust the total output from the farm that flows to the point of interconnection with the transmission system that connects it to the rest of the grid. This farm is viewed as one collective power plant for the purposes of forecasting, market dispatch, and utility planning.

especially solar, are far more likely than conventional resources to be distributed throughout the system, they can outperform voltage control from conventional, centralized facilities, even accounting for their local impacts on voltage.[34]

Increasing the Flexibility and Diversity of the Grid

Renewables can contribute to grid reliability and security by creating a grid that is more flexible—able to respond to system changes quickly—and diverse. Renewable generators also utilize new and free "fuel" resources (the wind and sun) and can be located in new places, both characteristics that can help create a more robust system.

Fuel Diversity

Fuel diversity in the electric system can help protect against fuel supply vulnerabilities, including supply shortages and price spikes. For example, coal- and gas-fired resources depend on the availability and deliverability of coal and natural gas, the supply of which can be affected by market prices and shortages, weather, and other factors. Coal usually is stored in large piles next to the power plant, but these can freeze solid at extreme winter temperatures; having other resources such as nuclear, natural gas, and renewable generators that can fill in when coal facilities are incapacitated ensures that power can continue to flow even during extreme conditions.

Renewable resources can also help insulate customers from fuel delivery and price constraints. The costs of fossil fuels are determined in part by markets, which can result in price spikes in response to fluctuating levels of supply or demand. Additionally, since natural gas production occurs in specific geographic regions of the country and gas flows through pipelines at a limited rate, pipeline constraints or failures can make it difficult to meet demand at all times.

Renewable energy fuels, such as wind and solar energy, are not dependent on pipelines, railroads, or other channels for delivery—simply siting generators in areas of good resource availability is sufficient to ensure an adequate fuel supply.

Renewable energy fuels, such as wind and solar, are not dependent on pipelines, railroads, or other channels for delivery—simply siting generators in areas of good resource availability is sufficient to ensure an adequate fuel supply. This not only ensures that some generation is not dependent on fuel delivery infrastructure, but can also help mitigate delivery constraints by displacing some local fossil fuel needs. By reducing demand for fossil fuels, renewables can also help moderate gas prices, resulting in additional cost savings for customers. Because renewable energy sources have no associated fuel costs and are not subject to market variability, they can also provide a valuable hedge against increases in fossil fuel prices.

Geographic Diversity

Renewable generators can increase the geographic diversity of generation, which can help strengthen the grid. A large conventional fossil-fired or nuclear facility might be 1,000 MW or more to take advantage of the economies of scale and operational efficiencies that come with size. Conversely, even large solar or wind installations rarely exceed 400 MW.[35] Renewable generation typically is spread over multiple, dispersed units. Their dispersion can, among many other advantages, reduce transmission energy losses, mitigate extreme events and system contingencies, mitigate weather and demand uncertainty, reduce the need for operating reserves and other ancillary services, and lower overall costs to electricity customers.[36]

Smaller, consumer-scale distributed energy resources also can provide significant grid reliability benefits if planned and sited correctly. These distributed energy resources are often renewable generators, since their solar and wind fuel is easily accessible and they do not create local pollution that may be subject to air permitting requirements (which may be especially stringent near large populations). For example, a study in the Western Interconnection found that increasing the use of distributed generation helps limit the impact of grid frequency disturbances.[37] Additionally, as discussed above, necessary reliability services such as reactive power must be produced close to where they are consumed. Distributed resources spread more evenly around load centers can help to maintain reactive power levels.

Conclusion

Reliable electric service is the backbone of our national economy. Renewable energy is the fastest-growing source of power generation in the electric sector. Maintaining and enhancing reliability while deploying new and cleaner renewable energy resources are twin imperatives.

The integration of new types of power into our grid while maintaining day-to-day reliability is not a new challenge for the industry. Our electric system has evolved over a century to adapt to changing patterns of energy supply and consumption while "keeping the lights on" with such remarkable consistency that we essentially take reliability for granted. Integration of solar and wind resources, whose output varies with the intensity of the sun and speed of the wind, is the next stage in this evolution of the grid, and it is occurring now.

While solar and wind power can add variability and uncertainty to the grid balancing act, the electric system is fully capable of integrating renewable generation at high levels. Already, forecasting and telemetry are helping to prepare grid managers for this variability and uncertainty, allowing wind and solar to be scheduled into the power grid more efficiently. Regions across the country have successfully deployed ever- higher levels of renewable resources. Advanced storage and integration technologies, better grid planning, and evolving markets are helping to shape a grid that is capable of integrating even more clean, renewable generation.

Renewable energy can strengthen the grid. Services provided by renewable generators include contributing to capacity and resource adequacy, maintaining local voltage and frequency performance, minimizing grid disturbances, providing grid balancing services, and creating a more flexible and diverse generation fleet. Renewable generators can be actively involved in shaping a clean, reliable electric system, in effect helping their own integration into the power system.

Renewable energy has moved beyond what many once saw as an uneasy coexistence with coal, gas, and nuclear power to a more multifaceted and more thoroughly integrated role where it provides essential reliability services similar to those from conventional thermal facilities. Ultimately, as wind and solar power levels increase, utilities, grid managers, and regulators will need to continue to ensure that systems have the right mix of resources to provide the full suite of reliability services necessary to keep the grid functioning. Renewable resources will be an important part of this reliability mix.

Glossary of Key Terms

Many definitions here are abridged or edited from the Glossary of Terms used in NERC Reliability Standards and the U.S. Energy Information Administration Glossary of Terms.

Alternating current (AC). A flow of electric charge that reverses its direction at regularly recurring intervals (as opposed to direct current). Most household devices are designed to connect to alternating current, and much of the transmission and distribution system transmits electricity in this form.

Ancillary services. Products used by system operators and grid managers to support reliability and transmission of electricity on the grid. These services can include frequency regulation, reactive power and voltage support, and various types of operating reserves. *See also* Reliability services.

Balancing area (BA). The entity responsible for maintaining balance of load, generation, and interchanges between its defined balancing area and other interconnected balancing areas, thereby supporting interconnection frequency and bulk power system reliability in real time. A balancing area also integrates long-term resource plans to ensure that there are enough resources and transmission for the system based on forecasts of future demand.

Bulk power system. The electrical generation resources, transmission lines, interconnections with neighboring systems, and associated equipment, generally operated at voltages of 100 kV or higher. Radial transmission facilities serving only one load with one transmission source are generally not included in this definition. Regulated by NERC; interstate components of the system are under FERC jurisdiction as well.

Capacity. The amount of power an energy generating resource is capable of producing. Capacity is measured in watts (kW, MW, GW, TW); each unit is 1,000 times greater than the previous (e.g., 1 GW is equal to 1,000 MW).

Capacity factor. The amount of electricity a unit produces relative to its total maximum output over a period of time (such as a year), expressed as a percentage. At a capacity factor of 75 percent, a unit with 100 MW of capacity will, on average, be providing 75 MW of power.

Capacity value. A value determined by a planning authority measuring what portion of total generator capacity can be counted on to contribute to serving load when most needed. This value is a function of many factors, including capacity factor, outage rates, timing of generation and critical operating hours, and other resources within the planning area.

Contingency (or contingency event). The unexpected failure or outage of a system component, such as a generator, transmission line, circuit breaker, switch, or other electrical element.

Contingency reserves. Capacity that may be deployed by a balancing area to respond to a contingency event or other contingency requirements.

Converter. A device that converts the voltage of an electric device. In electric power, this term is most commonly used for devices that convert alternating current to direct current (such as for use in battery applications or electronic devices).

Current. A flow of electric charge. In electric circuits, this charge is often carried by moving electrons in a wire. The rate at which current flows is measured in amps.

Curtailment. The intentional limitation of energy output from a generator. Often used to refer to renewable power that is available at the generator but cannot be delivered to load.

Demand. The amount of electricity required by end users at a specific time, or during a period of time. *See also* Load.

Demand response. Changes in electric usage by consumers in response to changes in electricity prices or requests from the system operator, often in exchange for incentive payments to induce lower electricity use at times of high wholesale market prices or when system reliability is in jeopardy.

Direct current (DC). A unidirectional flow of electric charge (as opposed to alternating current). Direct current is produced by some sources of electricity such as batteries and solar panels and is utilized for battery-powered appliances and many electronic devices. Some large transmission lines utilize direct current electricity, which experiences lower losses at high voltage over long distances than a comparable AC line.

Distributed energy resource (or distributed resource). A smaller resource (often less than 5 MW) that is distributed closer to where electricity is used. These resources are often distributed generators within the distribution system, such as at residential, commercial, or industrial locations, but can also include resources such as storage and demand response.

Distribution system. The portion of the wires and facilities of an electric system that is dedicated to delivering electric energy to the consumer; typically, this system operates between 4 and 35 kV. This system includes wires, transformers, substations, and other devices. Together with the transmission system, this constitutes the electric grid.

Electricity. The presence and flow of electric charge. This gives rise to a wide range of properties that, among other things, can be harnessed to manage energy and do useful work.

Energy. In the electrical context, the amount of electric power generated over a specific period of time, typically measured in kilowatt-hours, megawatt-hours, or gigawatt-hours (kWh, MWh, GWh); each unit is 1,000 times greater than the previous (e.g., 1 GWh is equal to 1,000 MWh).

Energy storage. Devices that can store electricity for later use. Includes batteries, flywheels, pumped hydroelectric storage, and other applications.

FERC. The Federal Energy Regulatory Commission, an independent agency that regulates the interstate transmission of electricity, natural gas, and oil. FERC has exclusive jurisdiction over the transmission and wholesale sale of electric energy in interstate commerce and over all facilities for such transmission or sale of electric energy.

Flexibility. The ability of an electric system to adapt to changing conditions in the system—demand, generation (variable and otherwise), and other factors—nimbly, cost-effectively, and reliably.

Frequency. The number of cycles an alternating current completes every second, measured in hertz (Hz). The standard power frequency for the U.S. is 60 Hz, or 60 cycles per second.

Frequency control. Actions deliberately or automatically undertaken to maintain an electric system's frequency at the desired value.

Generator. A facility that transforms a type of energy into electric power.

Governor. Electronic, digital, or mechanical device installed on most power plants that provides automatic (primary) frequency response by monitoring system frequency and (if activated) responding accordingly by proportionally increasing or decreasing generator output.

Independent system operator (ISO). An independent, FERC- and NERC-regulated entity established to coordinate regional transmission in a nondiscriminatory manner and ensure the safety and reliability of the electric system.

Inertia. Generally, in the electrical sense, the kinetic energy in rotating generators and motors that are connected and synchronized to the grid frequency. During a contingency event, this kinetic energy is immediately used to produce additional electric energy (although system frequency will fall as a result). Wind turbines can also use the inertia of their rotating blades and generators to immediately respond to such events.

Interconnection. Either:

- A geographic area in which the operation of bulk power system components is synchronized. When capitalized, any one of the four major electric system networks in North America and under the jurisdiction of NERC: Eastern, Western, ERCOT, and Quebec; or
- The point of connection between a generator and the electric system (which can be at either the transmission or distribution level).

Inverter. An electronic device or circuitry that changes direct current to alternating current. Used, among other applications, to convert the output from solar panels or batteries to alternating current that can be utilized or transmitted across the electric system.

Load. Another word for demand; used to refer to consumers of electricity and the energy they demand from the system.

Load shape (or demand shape). The pattern of electric demand, sometimes within a certain area or from a subset of customers, across a period of time.

NERC. North American Electric Reliability Corporation, a body tasked with maintaining the reliability of the bulk power system in most of the U.S. and Canada.

Non-spinning reserves. Generation not currently providing power to the system but capable of doing so, or interruptible load that can be removed from the system, within a specified time (usually within minutes).

Overgeneration. Generation that exceeds demand on an electric system; often discussed in the context of variable resources with output that exceeds the current demand, but also pertains to conventional resources that cannot reduce their output during periods when their output is not needed.

Peak demand (or peak). The maximum load on the grid in a specific period of time.

Power. The rate, per unit time, at which energy is available for consumption. *See* Capacity.

Ramp. An increase or decrease of electricity generation or consumption. “Fast ramping” resources are able to rapidly increase or decrease output or consumption and are necessary to respond to unforeseen changes in generation or demand.

Reactive power. A form of electrical power used on the grid to help maintain constant voltage in an AC power system (in addition to the “real power”). Adding reactive power to the system will increase voltage in the local portion of the electric grid, whereas reducing reactive power will lower local voltage. Reactive power is provided by generators, synchronous condensers, or electrostatic equipment such as capacitors. It is usually expressed in kilovars (kvar) or megavars (Mvar).

Regional transmission organization (RTO). Similar to an ISO, an independent, federally regulated entity established to coordinate regional transmission in a nondiscriminatory manner and ensure the safety and reliability of the electric system. FERC Order No. 2000 delineated twelve characteristics and functions that an entity must satisfy in order to become an RTO.

Reliability. A measure of the electric system’s ability to continue system operations and provide high-quality power to customers through a variety of conditions, even under system stress.

Reliability services. Services provided by components of the electric system (including generators, demand sources, and the transmission and distribution system) that help maintain normal operating conditions and reliability of the grid. Some of these services may be procured as ancillary services, although the term “essential reliability services” is increasingly used to refer to the broader set of such services.

Reserve margin. An amount of generation above the projected load that will be available in case demand exceeds planned supply.

Ride-through. The capability of a generator to continue operations through a frequency or voltage disturbance without disconnecting.

Smart grid. An electrical system that incorporates advanced and automated devices that can communicate with one another to optimize the functioning of the system. Such devices may include smart meters, advanced appliances, and automated equipment on generators.

Spinning reserves. Generation that is synchronized to the system frequency and ready to serve additional demand and demand fully removable from that system within a set period following a contingency event.

Telemetry. The process by which measurable electrical quantities from components of the electric system, including substations and generators, are instantaneously transmitted to grid operators, and vice versa.

Transformer. An electrical device for changing the voltage of alternating current.

Transmission system. An interconnected group of electric transmission lines and associated equipment for moving or transferring electricity in bulk between points of supply and points at which it is transformed for delivery over the distribution system to consumers. In the U.S., typically operated at voltages between 115 and 765 kV and in alternating current (though some very high voltage DC lines exist). Together with the distribution system, this constitutes the electric grid.

Trip point. The frequency or voltage deviation at which an electric device, such as a generator or motor, will disconnect from the grid.

Turbine. A machine for generating rotary mechanical power from the energy of a stream or fluid (such as water, steam, hot gas, or air), converting the kinetic energy of the fluids to mechanical energy, and then to electric energy (such as with a generator). Turbines are used in most fossil fuel–fired generators as well as wind generators.

Variability. The changing and sometimes uncertain characteristic of many demand and generation sources. Used often in the context of wind and solar resources, which have a weather-driven energy source and a therefore variable output.

Visibility. A characteristic of components on the electrical system (demand and generation sources, as well as other equipment and devices) that allows grid operators to see in real time the behavior of these components.

Voltage. The "pressure" in the electric system that determines the flow of electricity, driven by unequal distribution of electrical charges on the grid.

Voltage support. Actions deliberately or automatically undertaken to maintain an electric system's voltage at the desired value. This is most often accomplished through application of reactive power.

Endnotes

1. U.S. Department of Energy (U.S. DOE). Quadrennial Energy Review: Energy Transmission, Storage and Distribution Infrastructure. April 2015. Available at http://energy.gov/sites/prod/files/2015/04/f22/QER-ALL%20FINAL_0.pdf.
2. Center for Climate and Energy Solutions. Smart Grid Fact Sheet. Available at http://www.c2es.org/technology/factsheet/SmartGrid.
3. Edison Electric Institute. Actual and Planned Transmission Investment by Investor Owned Utilities (2009 – 2018). October 2015. Available at http://www.eei.org/issuesandpolicy/transmission/Documents/bar_Transmission_Investment.pdf.
4. The Brattle Group. Investment Trends and Fundamentals in US Transmission and Electricity Infrastructure. July 17, 2015. http://www.brattle.com/system/publications/pdfs/000/005/190/original/Investment_Trends_and_Fundamentals_in_US_Transmission_and_Electricity_Infrastructure.pdf?1437147799.
5. U.S. DOE. Annual U.S. Transmission Data Review. August 2015. http://www.energy.gov/sites/prod/files/2015/08/f26/Transmission%20Data%20Review%20August%202015.pdf.
6. North American Electric Reliability Corporation (NERC). M-1 Reserve Margins. http://www.nerc.com/pa/RAPA/ri/Pages/PlanningReserveMargin.aspx
7. PJM Interconnection. Data Viewer. Available at http://www.pjm.com/markets-and-operations/etools/dataviewer.aspx.
8. U.S. Energy Information Administration (EIA). Electric Power Monthly (November 2016 Data). January 26, 2017. Available at https://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_1_1.
9. Ibid.
10. U.S. EIA. Today in Energy (March 23, 2016). Available at http://www.eia.gov/todayinenergy/detail.php?id=25492.
11. U.S. EIA. Preliminary Monthly Electric Generator Inventory. January 26, 2017. Available at http://www.eia.gov/electricity/data/eia860M/.
12. *See* U.S. EIA. Table 4.7.B, Net Summer Capacity Using Primarily Renewable Energy Sources and by State, 2015 and 2014. Available at http://www.eia.gov/electricity/annual/html/epa_04_07_b.html. See California Solar Statistics. Monthly, Quarterly, and Annual Statistics. Available at https://www.californiasolarstatistics.ca.gov/reports/monthly_stats. See Solar Energy Industries Association (SEIA). State Solar Policy: California. Available at http://www.seia.org/state-solar-policy/california.
13. SEIA. Research & Resources: Solar Industry Data. Available at http://www.seia.org/research-resources/solar-industry-data.
14. Berkeley Lab. New Study Finds Price of Wind Energy in Us at an All-Time Low; Competitiveness of Wind Has Improved. August 18, 2014. Available at http://newscenter.lbl.gov/2014/08/18/new-study-finds-price-of-wind-energy-in-us-at-an-all-time-low-competitiveness-of-wind-has-improved/.
15. EIA. Annual Energy Review, Table 9.2. 2017. Available at https://www.eia.gov/totalenergy/data/annual/index.cfm#nuclear.

16. National Renewable Energy Laboratory (NREL). Clark, K., Milligan, M., King, J., Kirby, B., Guo, T., Liu, G. Examination of Potential Benefits of an Energy Imbalance Market in the Western Interconnection. March 2013. Available at http://www.nrel.gov/docs/fy13osti/57115.pdf.

17. Green Tech Media Research (GTM Research). U.S. Energy Storage Monitor: Q4 2016. Available at http://www.greentechmedia.com/research/subscription/u.s.-energy-storage-monitor2.

18. California Energy Commission. California Energy Storage Showcase. Available at http://www.energy.ca.gov/research/energystorage/tour/.

19. California ISO. Energy Imbalance Market Overview. Available at https://www.caiso.com/informed/Pages/EIMOverview/Default.aspx.

20. GTM Research and the Energy Storage Association. U.S. Energy Storage Monitor: 2015 Year in Review Executive Summary. March 2016. http://energytransition.umn.edu/wp-content/uploads/2016/04/US-Energy-Storage-Monitor-YIR-2015_Exec-Summary.pdf.

21. NREL. Lopez, A., Roberts, B., Heimiller, D., Blair, N. Porro, G. U.S. Renewable Energy Technical Potentials: A GIS-Based Analysis. July 2012. Available at http://www.nrel.gov/docs/fy12osti/51946.pdf

22. NREL. Estimating Renewable Energy Economic Potential in the United States: Methodology and Initial Results. August 2016. http://www.nrel.gov/docs/fy15osti/64503.pdf.

23. U.S. EIA. Today in Energy (November 4, 2015). Available at https://www.eia.gov/todayinenergy/detail.cfm?id=23632

24. American Wind Energy Association. The records keep falling: more new highs in wind energy output. February 23, 2016. Available at http://www.aweablog.org/the-records-keep-falling-more-new-highs-in-wind-energy-output/.

25. E3. Investigating a Higher Renewables Portfolio Standard in California. January 2014. Available at https://ethree.com/documents/E3_Final_RPS_Report_2014_01_06_with_appendices.pdf.

26. GE Energy Consulting (prepared for PJM Interconnection, LLC). PJM Renewable Integration Study: Executive Summary Report (Revision 05). March 31, 2014 (GE Consulting 2014). http://www.pjm.com/~/media/committees-groups/subcommittees/irs/postings/pris-executive-summary.ashx.

27. Federal Energy Regulatory Commission (FERC). Multi-Faceted Solution or Managing Flexibility with High Penetration of Renewable Resources. June 2013. Available at http://www.ferc.gov/CalendarFiles/20140411130433-T1-A%20-%20Navid.pdf

28. UVIG. Maggio, D. Methodology for Calculating Reserves in the ERCOT Market (presentation, UVIG Spring Technical Conference, San Diego, April 24–26, 2012). Available at variablegen.org/wp-content/uploads/2012/12/Maggio-Reserve_Calculation_Methodology_Discussion.pdf.

29. GE Energy Consulting 2014

30. Ibid.

31. Wind Energy Research Center. Naughton, J. Wind Diversity Enhancement of Wyoming/California Wind Energy Projects: Phase 2: A follow-on study concerning the effects of geographic diversity on overall impacts on California's renewable energy production. July 2015. Available at http://wyia.org/wp-content/uploads/2015/07/WIAWYCADivStdyPhsII_final.pdf.

32. Ernest Orland Lawrence Berkeley National Laboratory. Mills, A. and Wiser, R. Implications of Wide-Area Geographic Diversity for Short-Term Variability of Solar Power. September 2010. Available at https://emp.lbl.gov/sites/all/files/report-lbnl-3884e.pdf.

33. MacDowell, J., Dutta, S., Richwine, M., Achilles, S., and Miller, N. Serving the Future. IEEE Power & Energy Magazine (Volume 13, No 6). November/December 2015.

34. *See, e.g.,* IEEE. Vovos, P., Kiprakis, A., Wallace, A.R., Harrison, G. Centralized and Distributed Voltage Control: Impact on Distributed Generation Penetration. IEEE Transactions on Power Systems (Volume: 22, Issue: 1). February 2007. Available at http://ieeexplore.ieee.org/document/4077146/?tp=&arnumber=4077146&url=http:%2F%2Fieeexplore.ieee.org%2Fxpls%2Fabs_all.jsp%3Farnumber%3D4077146.

35. SEIA. Research & Resources: Major Solar Projects List. September 2016. Available at http://www.seia.org/research-resources/major-solar-projects-list.

36. The Brattle Group and WIRES. Chang, J., Pfeifenberger, J., Hagerty, J.M. The Benefits of Electric Transmission: Identifying and Analyzing the Value of Investments. July 2013. Available at http://wiresgroup.com/docs/reports/WIRES%20Brattle%20Rpt%20Benefits%20Transmission%20July%202013.pdf.

37. NREL. Miller, N.W., Shao, M., Pajic, S., D'Aquila, R. Western Wind and Solar Integration Study Phase 3—Frequency Response and Transient Stability. December 2014. Available at http://www.nrel.gov/docs/fy15osti/62906.pdf.