Photo by Dennnis Schroeder, NREL 31197

Explained: Fundamentals of Power Grid Reliability and Clean Electricity

Introduction

Maintaining reliability of the bulk power system, which supplies and transmits electricity, is a critical priority for electric grid planners, operators, and regulators. As we move toward a cleaner electricity system with more technologies like wind, solar, and battery storage, the way in which we plan for and achieve reliability will change. This document provides additional technical background to the topics covered in three fact sheets produced by the National Renewable Energy Laboratory (NREL) about grid reliability that explain how we measure, enforce, and plan for reliable systems with more clean electricity (NREL 2023a; 2023b; 2023c).

1 What Are the Elements of Grid Reliability?

1.1 What Is the Grid?

Major components of the power grid are illustrated in Figure 1 as part of two systems: (1) the bulk energy system consisting of generators and the high-voltage transmission network and (2) the distribution system, which includes the network of local lower-voltage power lines that deliver electricity to our homes and businesses.

1.2 How Is Reliability Defined?

Reliability encompasses many factors, summarized in Figure 2. Reliability is often measured and evaluated separately on the distribution network and the transmission/generation network. Components of bulk power system reliability include three elements that we refer to in this document as the "three R's": resource adequacy, operational reliability, and resilience (Geocaris 2022).

In the United States, the first two R's have definitions established by grid reliability organizations like the North American Electric Reliability Corporation (NERC):[1]

[1] For additional discussion of the concept of power system reliability, see NERC (2013b).

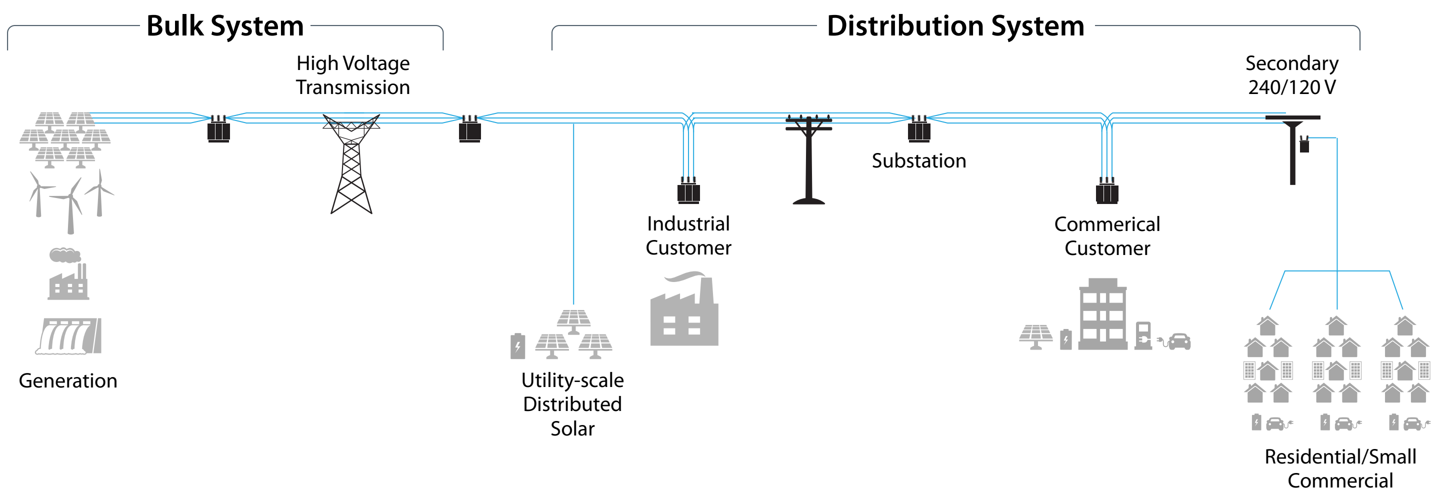

Figure 1. Major components of the grid

Resource adequacy is defined by NERC as "the ability of the electricity system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements" (NERC 2013a). This means the system can supply enough electricity—at the right locations—even during severe weather days and when unscheduled outages occur. All power plants and transmission lines occasionally fail, but an adequate system has sufficient spare capacity to come online and replace capacity that fails or needs to be taken out for maintenance.

Operating (or Operational) Reliability is defined by NERC as "the ability of the Bulk-Power System to withstand sudden disturbances, such as electric short circuits or the unanticipated loss of system elements from credible contingencies, while avoiding uncontrolled cascading blackouts or damage to equipment" (NERC 2013a). This means the system can balance supply and demand in real time, including maintaining the supply of electricity in the seconds and minutes during and immediately following a large power plant or transmission line failure (Denholm, Sun & Mai 2019). This ensures the lights stay on even when the unexpected occurs. Operational reliability also includes responses to normal, random variations in supply or demand, which may be referred to as the "flexibility" of power system operations.

The concepts of resource adequacy and operational reliability do overlap occasionally, but in general, resource adequacy focuses on having enough generators and transmission available

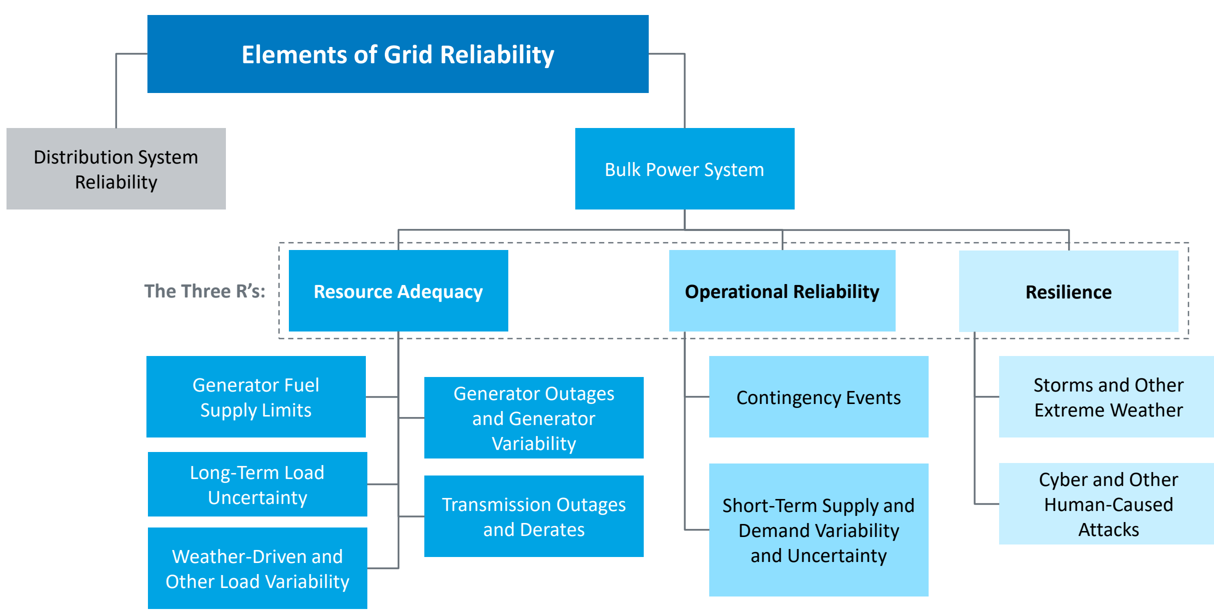

Figure 2. Reliability framework[2]

[2] This figure is based on an original published by Energy Systems Integration Group (2021a).

to meet demand, and operational reliability focuses on how those generators are operated in real time.

Resilience is less well-defined than the two other R's. The Federal Energy Regulatory Commission (FERC) defines resilience as "the ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event" (FERC 2018; Umunnakwe et al. 2021; EPRI 2020).

There is no clear distinction between resource adequacy and resilience. Generally, resource adequacy reflects statistical measures of a huge number of historical events based on normal and not-so-normal conditions (including extreme weather) (Novacheck et al. 2021), whereas resilience focuses on the most extreme events that are characterized by both high impact (or consequence) and low probability, typically affecting a large number of customers or geographic regions (National Academies of Sciences, Engineering, and Medicine 2017).

2 Who Establishes Reliability Standards?

Multiple institutions with overlapping jurisdictions and responsibilities establish and enforce resource adequacy standards. FERC oversees electric reliability of the bulk power system and delegates the development and most of the enforcement of standards to NERC. State public utility commissions also set resource adequacy standards for utilities operating under their jurisdictions. In regions with wholesale markets, regional transmission organizations and independent system operators use market mechanisms to provide reliability in grid operations and to ensure future transmission and generation capacity is available.

The power grid is designed around the trade-offs between costs and reliability and is expected to experience some level of outages on average.

The U.S. Department of Energy, FERC, NERC, regional planning authorities, utilities, power system operators, and other organizations work to ensure adequate reliability of the U.S. power system through the implementation of reliability standards, timely planning and investment, and effective system operations and coordination.

Within the United States, FERC has the highest-level oversight of electric reliability of the bulk power system, as outlined in the Federal Power Act (FERC 2020). FERC largely delegates the development and enforcement of standards to NERC but is responsible for approving those standards. FERC also approves rates related to the wholesale sale of electricity and transmission in interstate commerce—including infrastructure development used to create and transmit electricity—which impacts resource adequacy.

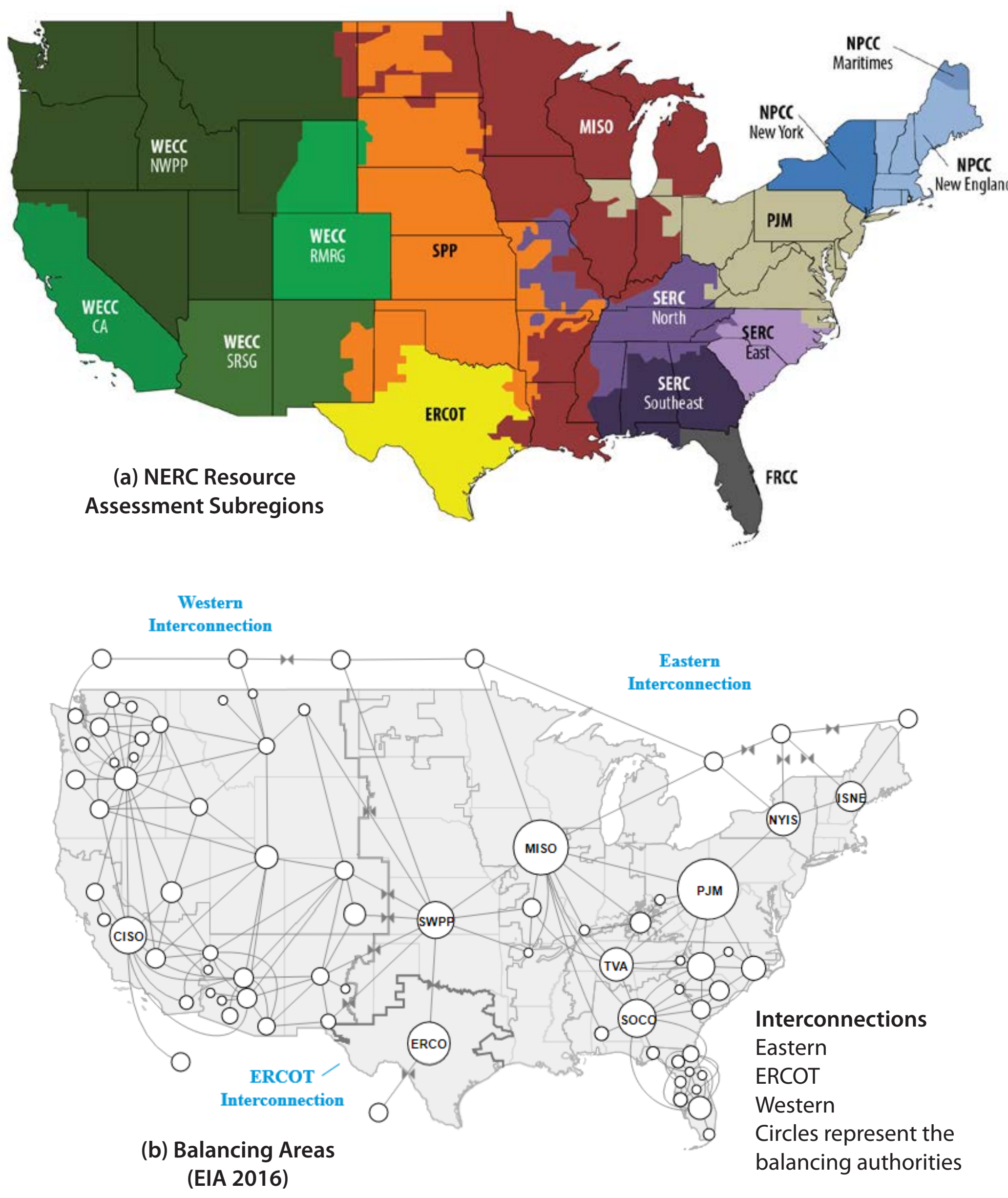

Figure 3. (a) NERC regional assessment areas and (b) balancing authority areas

NERC is a stakeholder-driven nonprofit that develops and enforces reliability standards for the bulk power system in the continental United States, Canada, and a portion of the Baja Peninsula of Mexico (Nevius 2020). NERC's current scope of responsibilities is derived from the 2005 Energy Policy Act, which directed FERC to designate an electric reliability organization, for which NERC was chosen. NERC generally focuses on process development, oversight, assessments of resource adequacy, long-term reliability forecasting, industry training, and auditing. The organization delegates most of the reliability standards development, compliance monitoring, and enforcement of reliability standards to regional entities. Some reliability standards are unique to regions while others apply to whole systems. All NERC decisions are approved by FERC and Canadian federal and province entities.

NERC's footprint is divided into six regions, each governed by a regional entity: the Midwest Reliability Organization, the Northeast Power Coordinating Council, Reliability First, SERC Reliability Corporation,[3] the Texas Reliability Entity, and the Western Electricity Coordinating Council.

NERC annually performs three resource adequacy assessments for the subregions shown in Figure 3(a). These include short-term assessments for the coming winter (NERC 2022a) and summer (NERC 2022b) peak periods and a long-term assessment that considers resource adequacy projections over the following decade (NERC 2022c). NERC also frequently issues topical reports on key issues related to reliability and reports on major reliability events.

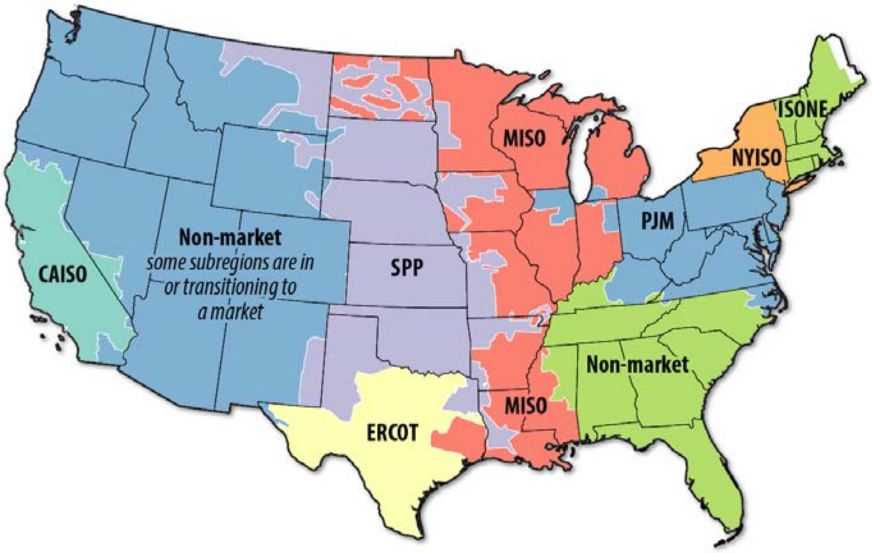

Figure 4. Wholesale energy markets in the United States (map generated by NREL)

Actual operation of the bulk power system is performed within 66 balancing authority areas within three electrically isolated interconnections: the Eastern Interconnection, Electric Reliability Council of Texas (ERCOT) Interconnection, and the Western Interconnection (Figure 3[b]).[4]

NERC planning regions and several large balancing authority areas overlap significantly. The U.S. Eastern Interconnection has 31 balancing authorities, and the U.S. Western Interconnection has 34 balancing authorities; the ERCOT interconnection also serves as a balancing authority. Some balancing authorities are operated by a wholesale market operator (an independent system operator [ISO] or regional transmission operator [RTO]). ISOs and RTOs manage more than two-thirds of the North American bulk power system and are responsible for dispatching generators, operating markets, and transmission planning (FERC 2020). Balancing authorities in non-ISO/RTO regions are typically run by large utilities.

Within the balancing authority areas, more than 3,200 utilities are responsible for generating and distributing electricity to consumers (U.S. Department of Energy 2016). Reliability standards for the distribution of electricity from the bulk power system to consumers are governed by state public utility commissions (PUCs). Most states address resource adequacy by requiring large investor-owned utilities to file long-term planning documents like integrated resource plans that include strategies for reliably meeting future demand. Integrated resource plans include load forecasts with plans for obtaining adequate generation through purchasing electricity or building more transmission and generation capacity (EPRI 2022). More recently, demand-side options for reducing electricity consumption in a utility's footprint may be included, particularly in states where utilities purchase power on the open market or through bilateral contracts instead of generating the power themselves. The planning time frame and the content of integrated resource plans vary widely, as do the types of utilities (such as investor-owned, municipals, cooperatives, and power suppliers) that must submit them. In some instances,

[3] SERC is no longer used as an acronym, but once stood for the Southeast Electric Reliability Council.

[4] The physical area is the balancing authority area (sometimes abbreviated as balancing area). The entity that operates the grid (maintains the real-time balance of supply and demand) in that region is the balancing area authority.

a PUC itself is responsible for submitting an integrated resource plan to a state legislature.

The U.S. electricity sector is divided into traditionally regulated markets and restructured competitive markets. In traditionally regulated markets, utilities generate, transmit, and distribute electricity to end customers.[5] The utility invests in assets subject to approval by its PUC, typically based on the portfolio of assets that can deliver reliable electricity at the lowest cost while meeting reliability and policy requirements.

Beginning in the late 1990s, the United States created restructured competitive markets in areas that now serve more than two-thirds of total electricity demand (FERC 2020). In restructured electricity markets, generators compete to provide electricity and ancillary services to load-serving entities. Each of the seven restructured markets in the United States (Figure 4) is organized under an RTO or ISO that sets rules regarding resource participation and market products. The creation of these markets has altered (to varying degrees) who sets the reliability requirements, methods of enforcement, and eligibility rules, and how generators providing resource adequacy services are incentivized.

All regions except ERCOT have explicit resource adequacy requirements. In some regions, ISOs/RTOs establish resource adequacy requirements to be met by load-serving utilities within their footprint. Load-serving entities can meet resource adequacy requirements through bilateral contracts, utility-issued requests for proposals, power purchase agreements with specific capacity availability clauses, or direct utility investment in generators. Load-serving entities in the California ISO (CAISO), the Midcontinent Independent System Operator (MISO), and the Southwest Power Pool (SPP) meet resource adequacy requirements primarily through such mechanisms (FERC 2020; EPRI 2022; CPUC 2022a). Resource adequacy requirements involve the RTO/ISO establishing capacity requirements for the load-serving entities within their authority.

Alternatively, in some regions, capacity can be purchased through a centralized auction by the grid operator on behalf of all load-serving entities in the RTO/ISO. In these auctions, the market clearing price is determined by the intersection of the supply curve with a precalculated demand curve (FERC 2020). Auctions generally take place several years out from the time period of obligation, and successive auctions are conducted to fulfill any new capacity needs that appear. The Independent System Operator-New England (ISO-NE), the New York Independent System Operator (NYISO), and PJM each have a capacity auction. MISO also has an optional centralized capacity auction for load-serving entities to procure capacity, and CAISO has a backstop capacity procurement auction.

When a generator's bid is accepted in a capacity auction, it receives the market clearing price in exchange for an obligation to be available to supply energy and to dispatch it by the ISO/RTO whenever called upon to support grid reliability. The capacity payment is usually expressed in terms of dollars per megawatt (MW) of capacity per day (or month), and it is made regardless of when and how many times the generator is called upon. During a reliability event, obligated generators are called on to supply their power to the wholesale energy market at the energy price prevailing during the event. In most markets, resources receive payment for both generation at the energy price and the capacity value, which they provide separately. Generators that underperform during an obligated period may be liable to pay penalties to the RTO/ISO for the portion of the capacity event during which they underperformed. As an example, PJM estimates about $1.8 billion in "non-performance charges" associated with underperformance during Winter Storm Elliot (PJM 2023), discussed in an NREL fact sheet about recent blackout events (NREL 2023c).

The Texas grid operator ERCOT does not have explicit resource adequacy requirements (FERC 2020). Instead, ERCOT relies on the economic principle of scarcity pricing—which leads to higher energy prices when supplies are scarce —to incentivize investment in, and operation of, adequate capacity. ERCOT also uses some voluntary bilateral contracts to ensure reliability.

While markets do not necessarily change the level of resource adequacy, they may provide additional incentives for new resources like demand-responsive loads to provide services.

3 How Do We Measure Grid Reliability?

3.1 Resource Adequacy Planning Metrics

Planning for resource adequacy starts with establishing a reliability target representing the desired level of reliability. No system can be 100% reliable, and increasing reliability also increases costs. Resource adequacy is often measured by the probability of an unserved load (also referred to as an interruption, load shed, or outage) due to an insufficient supply of generation capacity (Schlag et al. 2020). One common metric is the loss of load expectation (LOLE), or the expected

[5] Prior to regulatory changes, most electricity was provided by utilities that owned all distribution, generation, and transmission within a prescribed service territory. These include investor-owned (for-profit) utilities, municipal utilities, or cooperative utilities.

number of time periods that could face a supply shortfall. A commonly cited resource adequacy standard is 1 day of outages in 10 years (EPRI 2022). Another metric is the loss of load probability (LOLP), of the probability of an outage over a certain time period.

Once the resource adequacy target is established, planners determine the amount of capacity needed to achieve this target in the coming years. Forecasting and advance planning help ensure that utilities and developers have adequate lead time to bring new generators and supporting infrastructure online and respond to load growth and retiring generators. The amount of required capacity is often expressed in terms of a planning reserve margin that is designed to maintain sufficient capacity to address peak demand—with an extra amount of capacity to account for uncertainty in load growth and outages of generators and transmission lines (Energy Systems Integration Group 2021b).

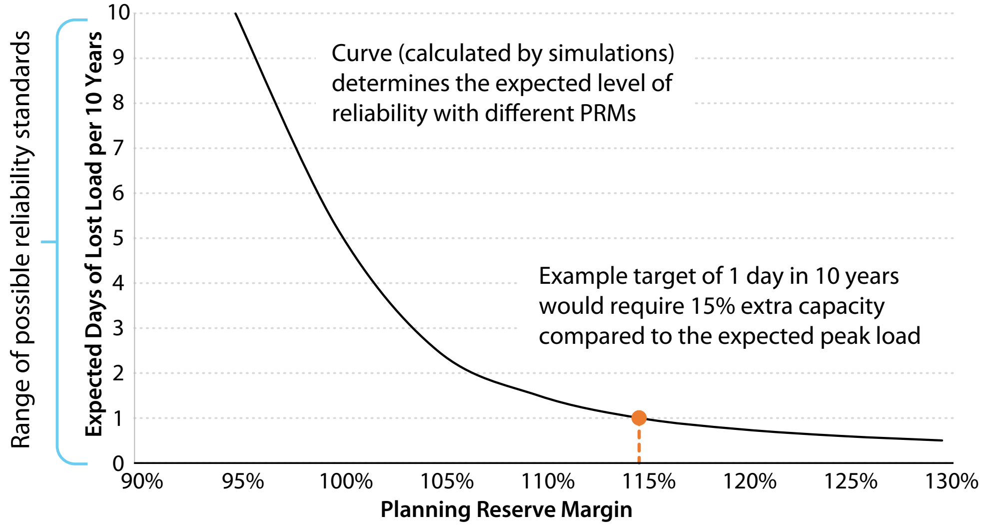

Figure 5. Establishing a planning reserve margin (PRM) based on the desired reliability standard (based on Schlag et al. [2020])

Table 1. Regional Resource Adequacy Standards

Assessment Area	Reference Margin Level	Assessment Area Terminology	Requirement?	Methodology	Reviewing or Approving Body
MISO	18.3%	Planning Reserve Margin	Yes: established annually	0.1 day/year LOLE	MISO[a]
NPCC-New England	13.4%–13.6%	Installed Capacity Requirement	Yes: three-year requirement established annually	0.1 day/year LOLE	ISO-NE, NPCC Criteria
NPCC-New York	20.0%[b]	Installed Reserve Margin	Yes: one-year requirement, established annually	0.1 day/year LOLE	NYSRC, NPCC Criteria
PJM	14.4%–14.8%	Installed Reserve Margin	Yes: established annually for each of three future years	0.1 day/year LOLE	PJM Board of Managers, ReliabilityFirst
SERC-Central/East/ Southeast	15.0%[c]	Reference Margin Level (RML)	No: NERC-applied 15%	0.1 day/year LOLE	Reviewed by Member Utilities
SERC-Florida Peninsula[d]	15.0%	Reliability Criterion	No: Guideline	0.1 day/year LOLP	Florida Public Service Commission
SPP	16.0%	Resource Adequacy Requirement	Yes: studied on biennial basis	0.1 day/year LOLE	SPP RTO Staff and Stakeholders
Texas RE-ERCOT	13.75%	Target Reserve Margin	No	0.1 day/year LOLE plus adjustment for non-modeled market considerations	ERCOT Board of Directors
WECC-CA /MX[e]	17.4%–19.0%	RML	No: Guideline	0.02% LOLP	WECC
WECC-WPP	13.5%–15.2%	RML	No: Guideline	0.02% LOLP	WECC[f]
WECC-SRSG	10.7%–12.4%	RML	No: Guideline	0.02% LOLP	WECC

[a] In MISO, the states can override the MISO planning reserve margin.
[b] For the capacity year beginning May 1, 2023 (New York ISO 2023).
[c] SERC does not provide RMLs or resource requirements for its sub-areas. However, SERC members perform individual assessments to comply with any state requirements.
[d] SERC-FP uses a 15% reference reserve margin as approved by the Florida Public Service Commission for non-IOUs and recognized as a voluntary 20% reserve margin criteria for IOUs; individual utilities may also use additional reliability criteria.
[e] California is the only state in the Western Interconnection that has a wide-area planning reserve margin (CPUC no date).
[f] WECC's Reference Margin Level in this table is for the hour of peak demand. Some hours in the year require a higher reserve margin to meet the 0.02% reliability criteria due to the variability in resource availability and resource performance characteristics.

An example of the relationship between a resource adequacy target and planning reserve margins shown in Figure 5. This relationship is established via simulations that add or remove generation capacity and measure how more or less frequent outages are likely to occur. As the planning reserve margins increased (more capacity is added), the frequency of expected outages drops. In this example, a utility has an LOLE target of 1 day in 10 years. To achieve this, a planning reserve margin of 15% is required. So, if the expected peak load is 1,000 MW, the utility would target 1,150 MW of dependable capacity (see Section 4 for further discussion of capacity). Accepting an expected loss of load of 2 days in 10 years would reduce the required planning reserve margin to about 7%, with a corresponding reduction in cost of building new generation.

Historically, capacity contributing to resource adequacy was provided primarily by a mix of hydropower and thermal (fossil fuel and nuclear) generation, and by a few other resources, including pumped storage hydropower and industrial interruptible load. The planning reserve margins designed in part to account for the fact that plants of all types incur outages, but as the contribution of variable generation resources has increased, there is a greater emphasis on analyzing the resource adequacy contribution from different resources. This change recognizes that not all capacity contributes an equal amount toward the planning reserve margin (discussed in detail in Section 4).

Table 1 summarizes regional resource adequacy requirements for NERC assessment areas. These are updated periodically to respond to issues such as increased volatility of demand due to extreme weather, and this list does not include subregions. For example, load-serving entities under the jurisdiction of the California Public Utilities Commission (CPUC), which covers about 85% of the state of California, must procure 16% reserve margin in 2023 and 17% in 2024 (CPUC 2022b).[6]

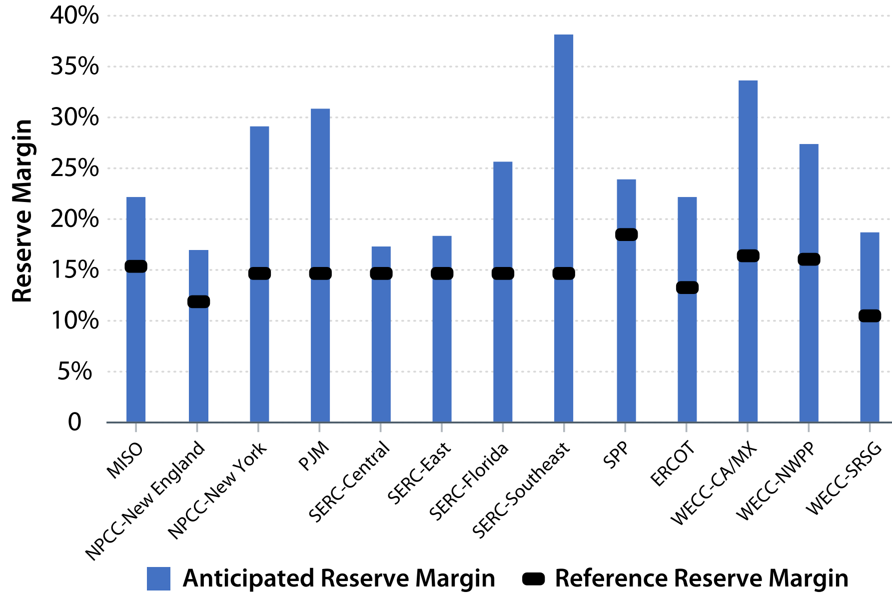

Figure 6. Regional planning reserve margins 2022

Resource adequacy of the U.S. power grid under normal conditions has remained above target levels in most regions based on the NERC assessment for the summer 2023 peak demand period, as illustrated in Figure 6 (NERC 2023b).[7] This figure includes the NERC reference (target) reserve margin, and the anticipated reserve margin, which accounts for the derated contribution of variable generation (discussed in Section 4).

3.2 Performance Metrics

As opposed to planning metrics such as planning reserve margins, performance metrics evaluate how well the grid actually performs. Individual utilities typically report customer outage data using three metrics (see Table 11.1 in U.S. Energy Information Administration [2022]):

- **System Average Interruption Duration Index (SAIDI).** The minutes of non-momentary electric interruptions per year that the average customer experiences.
- **System Average Interruption Frequency Index (SAIFI).** The number of non-momentary electric interruptions per year that the average customer experiences.
- **Customer Average Interruption Duration Index (CAIDI).** The average number of minutes it takes to restore non-momentary electric interruptions.

As discussed in an NREL fact sheet about current grid reliability (NREL 2023a), these metrics largely reflect the impact of distribution systems, but do capture loss of supply.

More detailed performance measures of the bulk system are reported by NERC and include several metrics (NERC 2022d). One metric is the frequency and duration of "energy emergency alerts" in three levels. Level 1 and Level 2 alerts indicate a period where there is growing potential for a shortfall in generation capacity, whereas a Level 3

[6] This includes derates for variable generation resources, which must be updated over time.

[7] In the 2022 Summer Reliability Assessment (NERC 2022b), NERC defined anticipated resources as including "generators and firm capacity transfers that are expected to be available to serve load during electrical peak loads for the season."

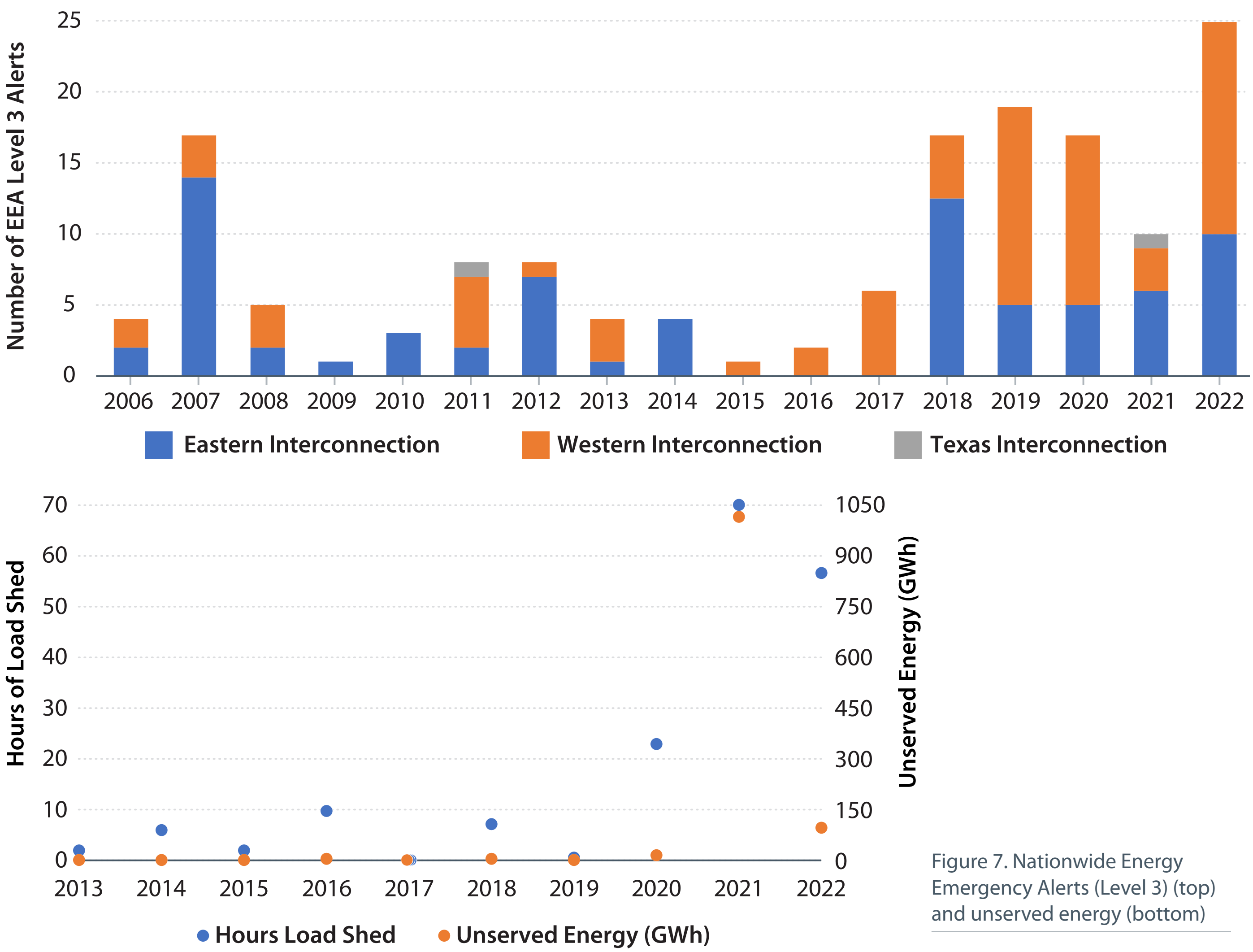

Figure 7. Nationwide Energy Emergency Alerts (Level 3) (top) and unserved energy (bottom)

alert indicates the possible need to shed load or the actual occurrence of load-shedding events. NERC also reports the duration of actual load-shed events and estimated amount of energy unserved.

Figure 7 (top) shows the number of Level 3 energy emergency events in North America from 2006 to 2022. From 2006 to 2017, there was an average of about five Level 3 alerts per year. From 2018 to 2022, there was a greater number of Level 3 alerts, driven largely by extreme weather. The increased amount of unserved energy in 2020–2022 was driven almost entirely by the three events discussed in the NREL fact sheet about recent blackouts (NREL 2023c).

4 What Is the Contribution of Individual Plants Toward Resource Adequacy?

Resource adequacy is a measure of the system as a whole, considering the total system demand and the combined contribution of all generators and the transmission network. No individual generation is 100% reliable, and ensuring resource adequacy means not just procuring enough generation, but also ensuring every generator's ability to contribute to resource adequacy is properly known and accounted for—even while preparing for increasing frequency and duration of extreme weather events (NOAA National Centers for Environmental Information 2023).

A critical factor in maintaining resource adequacy under a changing grid mix is the contribution of individual resources during all hours of the year, but particularly during periods of expected system stress such as hot summer afternoons (Energy Systems Integration Group 2023). The contribution of a generator that can be relied upon during periods of high system stress is known as its capacity credit.

4.1 Defining Capacity Credit

Capacity (also "nameplate capacity") generally refers to the rated output of a power plant when operating at maximum output. The capacity of individual power plants is typically measured in megawatts (MW).

Capacity credit is a measure of the contribution of a power plant to resource adequacy, meaning the ability of a system to reliably meet demand during all hours of the year. It is measured either in terms of capacity or as the fraction of its nameplate capacity (%), and it indicates the amount or portion of the nameplate capacity that is reliably available to meet load during times of highest system stress—typically the highest net-load hours of the year. Capacity credit may also be referred to as capacity value, but capacity value also sometimes refers to the monetary value of physical capacity (Mills and Wiser 2012). A similar term is effective load-carrying capability, which measures the increase in electrical load that can be accommodated by a generator while maintaining the same level of resource adequacy.

Note that the term capacity *factor* is a different measure of plant performance and does not by itself necessarily indicate the contribution of a plant toward resource adequacy. Capacity factor (given in percent) is a measure of how much energy is produced by a plant compared to its maximum output. It is calculated by dividing the total energy produced during a period by the amount of energy it would have produced if it ran at full output over that same period.

4.2 Capacity Credit of Thermal and Hydropower Resources

Studies of capacity credit show wide variation among generation resources. NERC tracks the availability of different resources in its Generator Availability Data System (NERC 2023a). Table 2 summarizes data from the 2021 Generator Availability Data System dataset. The Weighted Forced Outage Factor represents the fraction of time the unit experiences a forced outage, while the Weighted Equivalent Forced Outage Rate adds the effect of partial outages or derates. These data show a wide range of outage rates and plant availability. As a result, fossil plants do not provide resource adequacy capacity equal to their nameplate capacity (which is one of the major historical drivers behind use of a planning reserve margin), and there can be significant differences across technology types, with significant seasonal variation.

Table 2. Average Outage Rates by Power Plant Type (NERC 2023a)

Generator Category	# Units	Weighted Forced Outage Factor	Weighted Equivalent Forced Outage Rate
Coal Primary	460	8.9	12.3
Oil Primary	45	22.2	30.3
Gas Primary	246	14.7	20.3
Lignite Primary	17	7.3	13.0
Oil/Gas Primary	287	15.2	21.0
Nuclear	92	2.0	2.4
Jet Engine	189	32.6	35.0
Gas Turbine	523	28.7	30.9
Combined Cycle	305	3.2	4.5
Hydropower	893	5.2	5.3

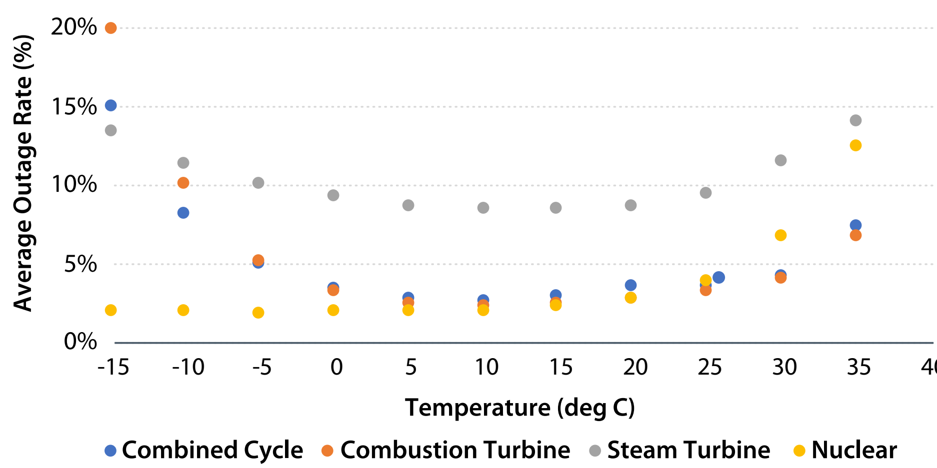

Figure 8. Historical outage rates for power plants as a function of temperature (Murphy, Lavin, and Apt 2020)

The actual capacity credit of thermal resources varies over time and can be substantially lower than average during periods of extreme heat or cold. Figure 8 provides an example of outage rates for four different thermal plant types using data from NERC as a function of temperature (Murphy, Lavin, and Apt 2020). The fossil plants show greater outage rates when temperatures fall below freezing. Outage rates for all types increase significantly when temperatures exceed about 30°C (86°F).

Hydropower plants typically have relatively low outage rates, and their contribution toward resource adequacy is driven more by water availability and type of hydropower plant (amount of stored water). Table 3 summarizes values NERC uses for the expected contribution during summer peak, showing significant regional variation, with values generally high in the eastern United States but as low as 33% in California.

Table 3. NERC-Reported Summer On-Peak Capacity Contribution of Hydropower by Reliability Region			
Assessment Area	**Nameplate Hydro (MW)**	**Expected Hydro (MW)**	**Expected % of Nameplate**
MISO	4,884	4,688	96%
NPCC-New England	3,565	2,472	69%
NPCC-New York	6,731	5,067	75%
PJM	3,027	3,027	100%
SERC-Central	4,967	3,315	67%
SERC-East	3,064	3,013	98%
SERC-Southeast	3,242	3,288	101%
SPP	5,465	4,996	91%
Texas RE-ERCOT	563	477	85%
WECC-CA/MX	13,957	4,606	33%
WECC-SW	1,202	844	70%
WECC-NW	41,860	22,752	54%
U.S. Total	91,964	58,068	63%

4.3 Capacity Credit of Wind, Solar, and Storage

Wind and solar are often referred to as "variable generation" resources. The growing role of these resources requires greater analysis of their contribution to resource adequacy and how it compares to traditional thermal and hydropower generators.

The limits on the ability of wind and solar to provide energy during peak periods has largely been incorporated into the planning process by major utilities and other grid planners. It is well understood that adding 1 MW of variable generation capacity does not provide 1 MW of capacity to the planning reserve margin, and planners do not assume that variable generation will act as a 1:1 replacement for thermal capacity.

Table 4 summarizes the regional summer capacity credits reported by NERC in their 2022 summer assessment. Wind energy potential in the United States tends to be lower than solar potential during hot, sunny afternoons that often drive the summer capacity credit values. The capacity credit of these resources, particularly solar, can decline as a function of deployment, and some of the values in Table 4 are higher than the value used by local planners. For example, the California Public Utilities Commission assumes solar (deployed without storage) provides a summer capacity credit of less than 15% due to significant deployment and a shift in net load to evening, compared to the 66% value used by NERC (CPUC 2022b).

There has been significant deployment of storage to provide resource adequacy capacity. The ability of storage to contribute to resource adequacy depends in part on its

Table 4. NERC-Reported Summer On-Peak Capacity Contribution of Wind and Solar by Reliability Region						
	Wind			**Solar**		
Assessment Area/ Interconnection	**Nameplate (MW)**	**Expected (MW)**	**Expected % of Nameplate**	**Nameplate (MW)**	**Expected (MW)**	**Expected % of Nameplate**
MISO	30,373	5,488	18%	7,499	3,750	50%
NPCC-New England	1,448	186	13%	2,914	1,163	40%
NPCC-New York	2,879	331	12%	179	84	47%
PJM	10,923	1,688	15%	5,169	2,984	58%
SERC-Central	1,206	564	47%	885	511	58%
SERC-East	0	0	NA	1,475	1,473	99%
SERC-Florida Peninsula	0	0	NA	7,724	4,534	59%
SERC-Southeast	0	0	NA	5,305	4,647	88%
SPP	32,028	4,500	14%	440	378	86%
Texas RE-ERCOT	30,938	10,293	33%	15,958	12,509	78%
WECC-CA/MX	9,362	1,111	12%	21,975	14,489	66%
WECC-SW	2,994	593	20%	3,493	1,411	40%
WECC-NW	20,296	3,968	20%	9,270	5,062	55%
U.S.	**111,509**	**18,429**	**17%**	66,328	40,486	61%

duration, or ability to discharge during periods of peak demand. Figure 9 shows the assumed capacity credit as a function of duration for PJM, and for several regions that use a 4-hour capacity rule, including CAISO, MISO, and NYISO.

The capacity credit of storage will change as the grid evolves and the shape of the net load curve changes (Denholm, Cole & Blair 2023). As more solar is deployed, the ability of 4-hour storage to meet the summer peak can increase. However, additional solar and storage can shift the period of greatest net load to winter, where longer-duration peaks act to decrease the capacity credit of storage.

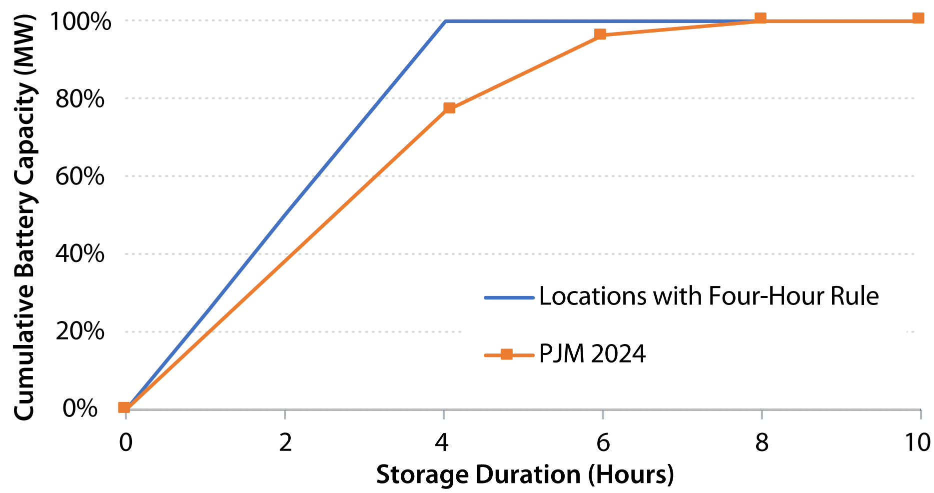

Figure 9. Capacity credit of storage as a function of duration in locations with 4-hour rule and PJM (using the effective load-carrying capability approach). This does not include forced outages.

4.4 Contribution of Non-Generation Resources

While system planners traditionally have relied on generators to provide the capacity to meet planning reserve margins, they have also relied on interregional transmission, energy efficiency, and flexible demand.

Transmission provides several benefits to ensuring resource adequacy. Transmission provides access to remote generation resources, but it can also add resource adequacy without the need for additional generation capacity. Transmission allows regions to share resources so that if a generator fails in one region, generators in another region can provide power to the affected area. This reduces the overall likelihood of an outage and allows regions to carry lower planning reserve margins for the same level of resource adequacy (ESIG 2023). Transmission can also link regions with non-coincident peak demand for electricity (such as the Northwest and California), therefore sharing resources and reducing the need for peaking capacity (Bloom et al. 2022).

Many resource adequacy assessments focus on meeting electricity demand with generation capacity despite the potentially large untapped resource of demand response, which could provide resource adequacy at lower costs than generation-only solutions.

Load flexibility and demand response have been a part of utility planning for decades, particularly for large industrial and commercial customers. These include "demand-based" or "interruptible" rates, where customers are charged a higher rate for usage during peak demand periods. This provides incentives for large industrial consumers to reduce demand during these periods, which, in turn, reduces the need for peaking capacity. Under interruptible rate structures, in exchange for offering lower electric rates, the utility reserves the option to limit or turn off electricity supply to the customer under certain defined circumstances. Utilities also offer demand response programs for residential customers. A common type is direct load control programs. Direct load control programs allow utilities to directly control certain appliances—most frequently air conditioners or electric water heaters—to reduce peak demand. In exchange for a reduction in the customer's bill, the utility installs a remotely controlled switch on the appliance and receives the right to occasionally turn off the appliances for short intervals, often 15 to 30 minutes.

The emergence of new technologies enables even greater opportunities for changing load shapes and reducing peak demand and therefore reducing the need for traditional capacity to meet resource adequacy requirements. Modern smart grid technologies have reduced meter and communication costs and can now provide consumers and utilities with information that better reflects the true costs of electricity consumption in end-user rates. Smart meters and appliances that "talk" to the utility and the end user allow for the use of innovative rate structures and other mechanisms to more cost-effectively balance electricity supply and demand. When prices are very high, smart appliances and devices could be programmed by the consumer to reduce load, reducing the need for new generation capacity. There are a variety of market mechanisms to enable demand response, including aggregation to create virtual power plants (Speetles, Lockhart, and Warren 2023).

The application of these technologies could simultaneously increase reliability for critical loads while decreasing the overall cost of energy.

5 What Are Other Reliability Challenges Associated With Large Amounts of Renewable Energy?

5.1 Resource Adequacy in 100% Clean Energy Systems

The NREL fact sheet "Explained: Maintaining a Reliable Future Grid With More Wind and Solar" (NREL 2023b) discusses maintaining resource adequacy with increased deployments of renewable resources and demonstrates how a mix of generation resources can maintain adequate reserve margins with appropriate planning. In the near term, maintaining adequate reserve margins will depend in part of the continued use of fossil-fueled peaking resources.

Approaching 100% clean systems will require replacing remaining fossil-fueled plants that provide primarily capacity services, but the amount replaced depends on many factors, including clean energy goals, eligible technologies, and technology progress. Figure 10 provides an example of the sources of peak capacity in scenarios of increasing renewables share in 2050. Even at a 95% reduction in carbon emissions (the center bar), remaining fossil fuel generators provide nearly half of the peak capacity during the summer.

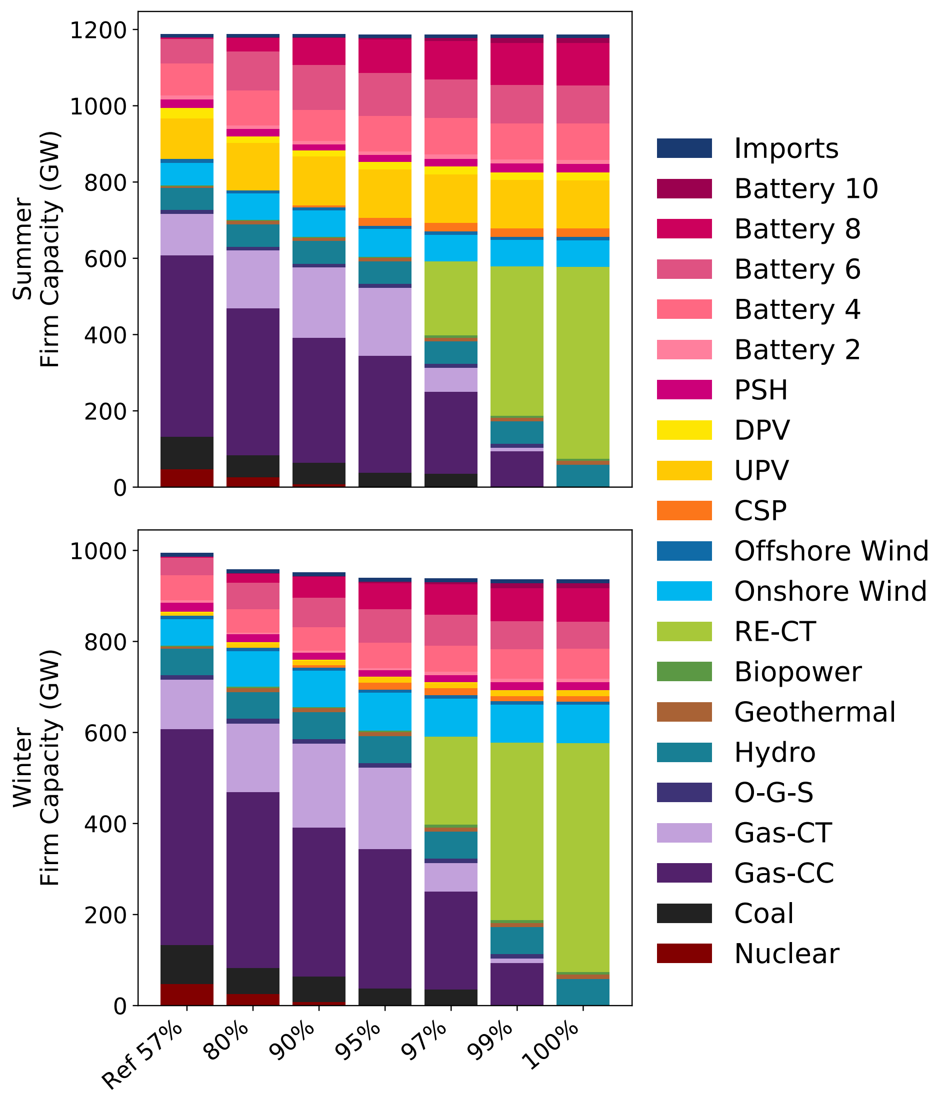

Figure 10. Firm capacity mix in the evolution to 100% clean energy

Moving beyond 95% clean energy (in this example) requires new sources of peaking capacity, particularly due to seasonal mismatch of renewable supply and normal demand patterns, which limits the contribution of variable generation plus diurnal storage. In this example, beyond 95% clean energy, the scenarios depend on seasonal storage, which in this case assumes the production of hydrogen or other storable fuels such as ammonia, then using those fuels in combustion turbines or fuel cells. It may be possible to maintain some fraction of the existing fossil fleet for periods of peak demand while offsetting emissions with direct air capture or negative emissions technologies. In scenarios without carbon offsets, other alternatives include a greater use of fossil plants with carbon capture, nuclear, or less variable renewable resources, including biomass, geothermal, new hydropower, and concentrating solar power with thermal storage/fuel backup.

5.2 Operational Reliability

Increased deployments of wind and solar resources have also raised concerns about how we maintain operational given the short-term fluctuations of wind and solar energy supply and the use of inverters, as opposed to the synchronous generators used in hydropower and thermal generators.

While the U.S. power grid is well below 100% variable renewable energy, several regions in the country (and many around the world) have achieved very high contributions from renewable energy over shorter timescales. This has demonstrated the ability to maintain operational reliability with new approaches and practices. Figure 11 illustrates the average and maximum hourly contribution from wind and solar resources for several regions (Millstein, O'Shaughnessy, and Wiser 2022). This does not include the contribution of rooftop or other behind-the-meter (BTM) solar, or other renewable or clean electricity resources.

The increase in variable generation has created the need for system operators to change how they maintain operational reliability, including how much reserves are procured and from where. There are two main concerns: (1) variability of resources over the minutes-to-hour timescales and (2) continued provision of frequency response, which addresses the most rapid variations in the subsecond-to-seconds timescales.

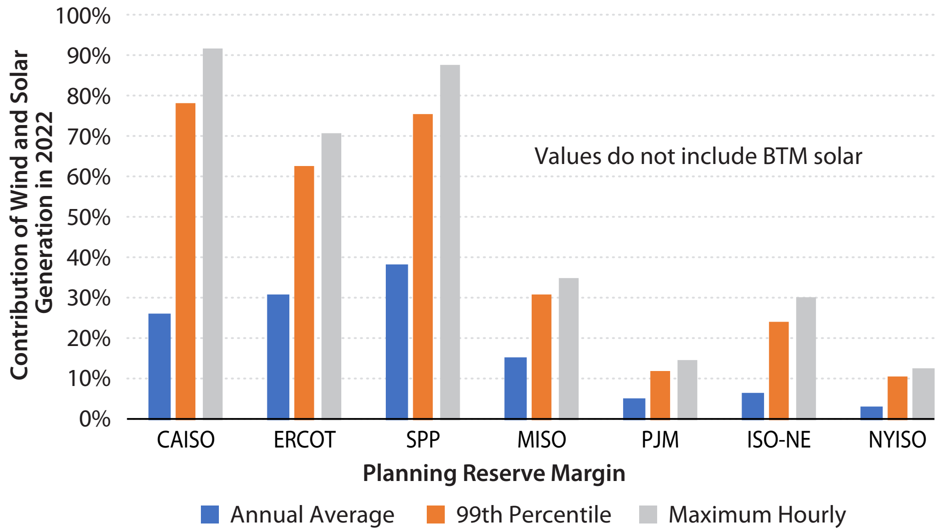

Figure 11. Average and maximum hourly contribution of wind and solar resources in 2022

The inherent variability of supply and demand in the seconds-to-minutes time frame is addressed by maintaining operating reserves, which are typically provided by generation capacity that can rapidly vary output. Greater amounts of variable generation increase the variability of net load due to fluctuations in output. This can lead to an increase in reserve requirements and was one of the initial concerns about large-scale deployment of variable generation—particularly the potential for increased expensive regulating reserves (Milligan et al. 2011). However, most ramping of variable generation does not occur on the shortest timescale (seconds). While the output of a single PV system can change rapidly due to passing clouds and individual wind turbines may rapidly vary, the aggregated output of many variable generation resources is much smoother. Supply and demand are balanced over large regions (see Figure 3), and transmission interconnections reduce the variability of overall net load, averaging out the short-term variability in variable generation. As a result, real-world experience demonstrates a modest increase in expensive regulating reserve requirements. Most variation occurs over the multiple-minute timescales, which is much easier to address, and in some cases, new "flexible ramping" reserve requirements have been implemented to address this variability. This requirement can be met with existing and new modern gas-fired generation and energy storage.[8] In many cases, variable generation is increasingly used to provide regulating and flexibility reserves by operating at partial output in a manner similar to the way in which conventional plants provide reserves.[9]

Decline in frequency response is a more recent concern (Denholm et al. 2020). Frequency response is needed to arrest the decline in frequency that can occur after the rapid failure of a large generator or transmission line and is traditionally provided by synchronous generators in thermal and hydropower plants. Wind, solar, and battery storage use power electronics (inverters) rather than synchronous generators to connect to the grid, and do not behave the same way as traditional thermal (fossil fuel and nuclear plants) and hydropower generation resources in the seconds and minutes following a grid event or disturbance. As a result, replacing conventional generation with variable generation resources typically reduces real inertia, reduces traditional frequency response, and can decrease the stability of the power system if no mitigating actions are taken.

System operators have identified multiple solutions to maintaining frequency response (EPRI 2019). In larger grids, such as the Eastern Interconnection, sufficient inertia and frequency response exists to mitigate any decline due to variable generation that will likely be deployed in the coming decade. A more significant problem occurs in much smaller systems, such as ERCOT, where declines in inertia during periods of high wind output have already required changes in planning and operation. The primary solution is the use of fast frequency response, which exploits the ability of electronic devices to respond very rapidly to changes in frequency. Fast frequency response is obtained from flexible loads, energy storage, and wind and solar (which can respond faster than conventional generators). Inverter-based resources are increasingly required to be able to provide grid services such as frequency response through state and federal standards. Additional

[8] CPUC also requires that capacity-meeting resource adequacy requirements be able to meet multi-hour ramping events (CPUC 2021).

[9] This requires the wind or sun to be available, but if it is not, then variable generation does not add any reserve requirements during that period of time.

inertia can be obtained from the use of synchronous renewable generators like hydropower, geothermal, biomass, and hydrogen-fueled turbines, and by converting retiring thermal plants into synchronous condensers.

Ultimately, a power system with increasing variable generation must be more flexible to balance supply and demand, but existing solutions have maintained high levels of operational reliability. The continued use of existing solutions, along with several emerging technologies, are expected to maintain this level of operational reliability in the coming decade.

6 Where Can I Find Out More?

- Reliability Assessments (NERC): https://www.nerc.com/pa/RAPA/ra/Pages/default.aspx
- U.S. Energy Information Adminstration reliability statistics by utility: Form EIA-861, Annual Electric Power Industry Report: https://www.eia.gov/electricity/data/eia861/
- Power Grid Reliability Basics (NREL): https://www.nrel.gov/research/power-grid.html

References

Bloom, Aaron, Josh Novacheck, Greg Brinkman, James McCalley, Armando Figueroa-Acevedo, Ali Jahanbani-Ardakani, Hussam Nosair, et al. 2022. "The Value of Increased HVDC Capacity Between Eastern and Western U.S. Grids: The Interconnections Seam Study." *IEEE Transactions on Power Systems* 37(3): 1760–1769. https://doi.org/10.1109/TPWRS.2021.3115092.

[CPUC] California Public Utilities Commission. 2021. 2022 *Filing Guide for System, Local and Flexible Resource Adequacy (RA) Compliance Filings*. R.19-11-009. https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/resource-adequacy-homepage/resource-adequacy-compliance-materials/final-2022-ra-guide-clean-101821.pdf.

CPUC. 2022a. "Reliability & Other Filing Requirements for Load Serving Entities' 2022 Integrated Resource Plans – Approach." https://www.cpuc.ca.gov/-/media/cpuc-website/divisions/energy-division/documents/integrated-resource-plan-and-long-term-procurement-plan-irp-ltpp/2022-irp-cycle-events-and-materials/20220407-fr-and-reliability-mag-slides.pdf.

CPUC. 2022b. *Decision Adopting Local Capacity Obligations for 2023–2025, Flexible Capacity Obligations for 2023, and Reform Track Framework*. Decision 22-06-050. https://docs.cpuc.ca.gov/PublishedDocs/Published/G000/M488/K540/488540633.PDF.

CPUC. No date. "Resource Adequacy Homepage." https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/electric-power-procurement/resource-adequacy-homepage.

Denholm, Paul, Wesley Cole, and Nate Blair. 2023. Moving Beyond 4-Hour Li-Ion Batteries: Challenges and Opportunities for Long(er)-Duration Energy Storage. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A40-85878. https://www.nrel.gov/docs/fy23osti/85878.pdf.

Denholm, Paul, Trieu Mai, Rick Wallace Kenyon, Ben Kroposki, and Mark O'Malley. 2020. *Inertia and the Power Grid: A Guide Without the Spin*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-73856. https://www.nrel.gov/docs/fy20osti/73856.pdf.

Denholm, P., Y. Sun, T. T. Mai, 2019 *An Introduction to Grid Services: Concepts, Technical Requirements, and Provision from Wind* (National Renewable Energy Lab. (NREL), Golden, CO https:/doi.org/10.2172/1505934.

Energy Information Administration 2016. *U.S. electric system is made up of interconnections and balancing authorities* https://www.eia.gov/todayinenergy/detail.php?id=27152

Energy Systems Integration Group. 2021a. *Redefining Resource Adequacy for Modern Power Systems*. A Report of the Redefining Resource Adequacy Task Force. Reston, VA. https://www.esig.energy/reports-briefs/.

Energy Systems Integration Group. 2021b. *Ensuring Not Only Clean Energy, but Reliability: The Intersection of Resource Adequacy and Public Policy*. A Report of the Redefining Resource Adequacy Task Force. Reston, VA. https://www.esig.energy/download/ensuring-not-only-clean-energy-but-reliability-the-intersection-of-resource-adequacy-and-public-policy/.

Energy Systems Integration Group. 2023. *Ensuring Efficient Reliability: New Design Principles for Capacity Accreditation*. A Report of the Redefining Resource Adequacy Task Force. Reston, VA. https://www.esig.energy/new-design-principles-for-capacity-accreditation/.

EPRI. 2020. "Power System Supply Resilience: The Need for Definitions and Metrics in Decision-Making." https://www.epri.com/research/products/000000003002014963.

EPRI. 2022. "Resource Adequacy for a Decarbonized Future." https://www.epri.com/research/products/000000003002022192.

EPRI. 2019. "Meeting the Challenges of Declining System Inertia." Technical Update 3002015131. Palo Alto, CA: Electric Power Research Institute. https://www.epri.com/research/products/000000003002015131.

[FERC] Federal Energy Regulatory Commission. 2018. *Grid Resilience in Regional Transmission Organizations and Independent System Operators*, AD18-7-000. https://cms.ferc.gov/sites/default/files/CalendarFiles/20180108161614-RM18-1-000.pdf.

FERC. 2020. *Energy Primer: A Handbook for Energy Market Basics*. Washington, D.C.: Federal Energy Regulatory Commission. https://www.ferc.gov/sites/default/files/2020-06/energy-primer-2020_0.pdf.

Geocaris, Madeline. 2022. "Assessing Power System Reliability in a Changing Grid, Environment." National Renewable Energy Laboratory. https://www.nrel.gov/news/program/2022/assessing-power-system-reliability-in-a-changing-grid-environment.html.

Milligan, M., Erik Ela, Bri-Mathias Hodge, Brendan Kirby, Debra Lew, Charlton Clark, Jennifer DeCesaro, Kevin Lynn, Integration of Variable Generation, Cost-Causation, and Integration Costs, The Electricity Journal, Volume 24, Issue 9, 2011, Pages 51-63, ISSN 1040-6190

Mills, Andrew, and Ryan Wiser. 2012. *Changes in the Economic Value of Variable Generation at High Penetration Levels: A Pilot Case Study of California*. Berkeley, CA: Lawrence Berkeley National Laboratory. https://www.osti.gov/servlets/purl/1183176.

Dev Millstein, Eric O'Shaughnessy, Ryan Wiser. 2022. Renewables and Wholesale Electricity Prices (ReWEP) tool. Lawrence Berkeley National Laboratory. Version 2023.1 https://emp.lbl.gov/renewables-and-wholesale-electricity-prices-rewep

Murphy, Sinnott, Luke Lavin, and Jay Apt. 2020. "Resource Adequacy Implications of Temperature-Dependent Electric Generator Availability." *Applied Energy* 262: 114424. https://doi.org/10.1016/j.apenergy.2019.114424.

National Academies of Sciences, Engineering, and Medicine. 2017. *Enhancing the Resilience of the Nation's Electricity System*. Washington, DC: The National Academies Press. https://doi.org/10.17226/24836.

[NERC] North American Reliability Electric Corporation. 2013a. "Reliability Terminology: August 2013." https://www.nerc.com/AboutNERC/Documents/Terms%20AUG13.pdf.

NERC. 2013b. "VIA Electronic Filing: Re: Informational Filing on the Definition of Adequate Level of Reliability." https://www.nerc.com/pa/Stand/Resources/Documents/Adequate_Level_of_Reliability_Definition_(Informational_Filing).pdf.

NERC. 2022a. "2022–2023 Winter Reliability Assessment." https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_WRA_2022.pdf.

NERC 2022b. "2022 Summer Reliability Assessment." https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_SRA_2022.pdf.

NERC. 2022c. "2022 Long-Term Reliability Assessment." https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2022.pdf.

NERC. 2022d. 2022 *State of Reliability: An Assessment of 2021 Bulk Power System Performance*. https://www.nerc.com/pa/RAPA/PA/Performance%20Analysis%20DL/NERC_SOR_2022.pdf.

NERC. 2023a. "Generating Availability Data System (GADS). https://www.nerc.com/pa/RAPA/gads/Pages/GeneratingAvailabilityDataSystem-(GADS).aspx.

NERC 2023b. "2023 Summer Reliability Assessment." https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_SRA_2023.pdf.

Nevius, D. 2020. The History of the North American Electric Reliability Corporation. https://www.nerc.com/AboutNERC/Resource%20Documents/NERCHistoryBook.pdf.

New York ISO. 2023. "How the Installed Reserve Margin Supports Reliability in New York." https://www.nyiso.com/-/how-the-installed-reserve-margin-supports-reliability-in-new-york.

NOAA National Centers for Environmental Information. 2023. "U.S. Billion-Dollar Weather and Climate Disasters." https://www.ncei.noaa.gov/access/billions/. DOI: 10.25921/stkw-7w73.

Novacheck, Josh, Justin Sharp, Marty Schwarz, Paul Donohoo-Vallett, Zach Tzavelis, Grant Buster, and Michael Rossol. 2021. *The Evolving Role of Extreme Weather Events in the U.S. Power System With High Levels of Variable Renewable Energy*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-6A20-78394. https://www.nrel.gov/docs/fy22osti/78394.pdf.

[NREL] National Renewable Energy Laboratory. 2023a. "Explained: Reliability of the Current Power Grid." Golden, CO: National Renewable Energy Laboratory. NREL/FS-6A40-87297. https://www.nrel.gov/docs/fy24osti/87297.pdf.

NREL. 2023b. "Explained: Maintaining a Reliable Future Grid With More Wind and Solar." Golden, CO: National Renewable Energy Laboratory. NREL/FS-6A40-87298. https://www.nrel.gov/docs/fy24osti/87298.pdf.

NREL. 2023c. "Explained: Causes of Three Recent Major Blackouts and What Is Being Done in Response." Golden, CO: National Renewable Energy Laboratory. NREL/FS-6A40-87308. https://www.nrel.gov/docs/fy24osti/87308.pdf.

PJM. 2023. *Winter Storm Elliott Event Analysis and Recommendation Report*. https://pjm.com/-/media/library/reports-notices/special-reports/2023/20230717-winter-storm-elliott-event-analysis-and-recommendation-report.ashx.

Schlag, N., Z. Ming, A. Olson, L. Alagappan, B. Carron, K. Steinberger, and H. Jiang. 2020. "Capacity and Reliability Planning in the Era of Decarbonization: Practical Application of Effective Load Carrying Capability in Resource Adequacy," Energy and Environmental Economics, Inc. https://www.ethree.com/elcc-resource-adequacy/.

Speetles, Brittany, Eric Lockhart, and Adam Warren. 2023. Virtual Power Plants and Energy Justice. Golden, CO: National Renewable Energy Laboratory. NREL/TP-7A40-86607. https://www.nrel.gov/docs/fy24osti/86607.pdf.

Umunnakwe, A., H. Huang, K. Oikonomou, and K. R. Davis. 2021. "Quantitative Analysis of Power Systems Resilience: Standardization, Categorizations, and Challenges." *Renewable and Sustainable Energy Reviews* 149: 111252. https://doi.org/10.1016/j.rser.2021.111252.

U.S. Department of Energy. 2016. *Maintaining Reliability in the Modern Power System* https://www.energy.gov/policy/articles/maintaining-reliability-modern-power-system

U.S. Energy Information Administration. 2022. *Electric Power Annual*. Washington, D.C. U.S. Energy Information Administration. https://www.eia.gov/electricity/annual/.

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