Maintaining Grid Reliability – Lessons from Renewable Integration Studies

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National Renewable Energy Laboratory

NREL is a national laboratory of the U.S. Department of Energy
Office of Energy Efficiency & Renewable Energy
Operated by the Alliance for Sustainable Energy, LLC

Contract No. DE-AC36-08GO28308

Technical Report
NREL/TP-5C00-89166
April 2024

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Suggested Citation
Denholm, Paul, Ilya Chernyakhovskiy, and Lauren Streitmatter. 2024. *Maintaining Grid Reliability – Lessons from Renewable Integration Studies*. Golden, CO: National Renewable Energy Laboratory. NREL/TP-5C00-89166.
https://www.nrel.gov/docs/fy24osti/89166.pdf.

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Golden, CO 80401
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Acknowledgments

The authors would like to thank the following individuals for their contributions. Editing and other communications support was provided by Amy Brice, Liz Breazeale, Madeline Geocaris. Helpful review and comments were provided by Paul Donohoo-Vallett, Bahram Barazesh, Patrick Brown, Jaquelin Cochran, Jeffery Dennis, Jason Frost, Trieu Mai, Glenda Oskar, Sohum Pawar, Gian Porro, Eric Rollison, Mark Ruth, Paul Spitsen, and Ryan Wiser.

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1 Introduction

In 2023, clean energy resources (including renewables and nuclear power) provided about 41% of electricity in the United States, with more than 16% of total generation provided by wind and solar—called “variable” renewable energy sources because of their daily and seasonal fluctuations in availability (U.S. Energy Information Administration 2024). The bulk power system, which supplies and transmits electricity, maintained high reliability throughout the year, showing that grid reliability is achievable as deployment of wind and solar has increased.

Wind and solar contributions to the nation’s electricity mix are projected to grow significantly—Gagnon et al. (2024) project that wind and solar could provide more than 60% of national electricity generation by 2035 under existing polices. Maintaining high reliability in the bulk power system while increasing renewable resource deployment is a critical priority for electric grid planners, operators, and regulators.

The U.S. Department of Energy (DOE) and other organizations have sponsored numerous research studies over the last two decades to examine the effect of increased wind and solar deployment on grid reliability, including a number of studies that examine grids deriving more than 50% of annual energy from wind and solar. Here, we discuss key findings from both the research body of knowledge and real-world practice related to grid reliability, and we demonstrate how to plan for and achieve continued reliability in the future as wind and solar deployment increase.

1.1 Three Key Issues To Maintaining Bulk System Reliability With Increased Wind and Solar

Maintaining bulk system reliability requires balancing the supply of electricity with demand at various timescales, from less than a second to hours, days, and beyond.[1] Maintaining reliability with increased deployment of wind and solar at scale presents issues that can be summarized into three general categories:

1. **Responding to short-term variability of wind and solar generation.** The fluctuation of variable renewable energy supply was one the first concerns with wind and solar deployment. Output from these resources can vary over multiple timescales from seconds to hours with limited predictability. This variability and uncertainty can impact how the system is operated, so there has been considerable effort to study ways to mitigate these impacts.

2. **Ensuring enough generation to meet demand during all hours of the year.** Grid planners traditionally focused on meeting demand during peaks, like hot summer afternoons and cold winter nights. But with the growth of wind and solar, focus has shifted to maintaining an adequate mix of resources to meet demand in all hours, particularly where renewables are expected to replace traditional fossil-fueled generators.

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[1] For additional discussion of the concept of power system reliability (including formal definitions of reliability elements), see North American Electric Reliability Corporation (2013).

Planning is further complicated by the impact of new loads from electrification, which can also shift the timing of peak demands.

3. **Maintaining stability in the event of a grid disturbance.** One aspect of grid stability that relates to the deployment of wind and solar is frequency stability, or the ability to avoid large changes in frequency after a generator or transmission line failure. The concern is associated with the loss of traditional system inertia as renewable resources like wind and solar displace fossil-fueled resources, whose operating characteristics inherently provide inertia.[2]

1.2 Summary of Findings

Dozens of studies address various aspects of reliability with the increased deployment of renewable energy resources in regions across the United States. The studies examine contributions from renewables that range from 30% to 100% of total generation and show that these systems can achieve a desired level of reliability if appropriate measures are taken to change how the grid is planned and operated. These measures can be summarized in four categories:

1. **Short-term variability and uncertainty in renewable generation can be managed cost-effectively by increasing grid flexibility.** Many grid flexibility options have been deployed, including changing how the power system is scheduled, balancing supply and demand over larger regions, using energy storage and other quick-ramping resources, and employing new operating reserve approaches.
2. **Demand for electricity during all hours of the year can be met through a portfolio approach.** A portfolio approach aggregates variable renewable deployment with dispatchable resources like energy storage, existing and new fossil resources, and new "clean firm" technologies. Studies highlight the benefits of combining solar and storage to meet summer peaks. These studies also demonstrate that significant renewable resource contributions and deep decarbonization can occur as existing (and new) fossil resources transition from sources that provide energy during many hours of the year to resources that operate primarily during periods of low wind or solar output. Systems studies that approach or reach 100% clean energy demonstrate how clean firm technologies can replace existing fossil resources that are acting primarily as capacity resources.
3. **Increased utilization of power electronics supports frequency stability.** Frequency stability studies have demonstrated that grids can maintain reliable operation with greatly increased use of wind and solar. Along with energy storage, wind and solar resources use power electronics that can react very quickly to faults and provide frequency support to the grid—which can offset the decline in inertia.

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[2] While this list covers most of the important issues evaluated in renewable integration and reliability studies, it is not comprehensive. There are other important issues that have been studied and some that require further study. These include voltage control and stability, system strength, transient stability, and fault current. These issues are not discussed further in this report.

4. **Expanded transmission networks are central to increasing reliability.** Capacity expansion and chronological operational studies generally conclude that increased utilization of existing transmission and new transmission expansion are needed to cost-effectively achieve high contributions of wind and solar across the United States. This includes building out local transmission networks to access the best renewable energy resources as well as expanding transmission capacity between balancing areas and interconnections to move power from where it is available to where it is most needed. This also acts to reduce variability of the aggregated supply of renewable resources across various timescales.

These findings have been incorporated into current utility practices, which has led to instantaneous contributions of wind and solar of over 80% in several regions of the United States (Millstein, O'Shaughnessy, and Wiser 2023). Current utility plans now incorporate various approaches to achieving increased economic deployments of wind and solar while maintaining reliability standards.

1.3 How Have We Studied the Evolving Grid?

Dozens of studies have been performed that examine one or more of the three key issues using a variety of tools and approaches, but they have some common elements.[3] They generally start with establishing the scenarios to be studied, including the generation mix in some future year. The scenarios can be developed manually or by using a capacity expansion model that identifies the optimal (least-cost) mix of resources that can meet the target grid conditions.[4]

Once the future resource mix and study conditions are established, a variety of tools may be used, depending on the study goal:

- **Variability studies** are used to evaluate how the mix of generation, storage, and transmission resources can respond to variations in supply from wind and solar.[5] Many of the earliest studies were designed to examine the avoided costs that result from reduced output from fossil-fueled plants. They often focus on the impact of variability on the existing fossil-fueled generation fleet to ensure the system can react quickly enough and provide adequate levels of operating reserves. The studies also often examine the impact on power plant costs as the plants spend more time varying output and more frequently stop and start. Variability studies use a production cost model that simulates the chronological operation of the grid at an hourly (or sub-hourly) resolution and calculates the cost of operating the system.[6] These studies typically evaluate reliability over a single year using historical weather patterns.
- **Resource adequacy studies** evaluate the probability that there will be unserved energy (power outages) that might result from some combination of insufficient supply of

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[3] A more detailed description of study methods is provided in Katz and Chernyakhovskiy (2020).

[4] Capacity expansion models are not unique to renewable studies. They have been used as part of utility planning processes for decades. For additional discussion see Murphy and Weiss (1990) and Cole et al. (2017).

[5] While production cost models typically do not simulate the more rapid variations in supply in the regulation time frame, they do ensure adequate reserves can respond to more rapid variation.

[6] These tools use detailed datasets that include individual generator performance and how fast they can vary output.

generation resources or higher-than-average demand.[7] These studies often include additional consideration of forecasted changes to demand patterns due to energy efficiency and electrification of end uses. The studies perform chronological simulations over at least one year of future grid conditions, examining in detail the potential shortfall of supply and potential mitigation measures during periods of high demand and during periods of lower renewable energy supply, often using the same production cost models as variability studies. However, resource adequacy studies may also use additional tools that consider uncertainty in resources over longer time periods and a broader set of possible weather conditions (or use a single tool that combines both chronological simulations with the probabilistic component).

- **Frequency stability studies** examine the ability of the grid to maintain system frequency within a tolerance. Unlike the previous studies that examine one or more full years, these studies typically only consider a few moments in time, often those where the system may be particularly vulnerable to a fault, such as periods where many thermal generators have been turned off and there is less inertia on the grid. They use a class of tool known as a power flow model to simulate the dynamic operation of the grid immediately following a fault and can identify conditions where frequency stability may be compromised.[8]

It is important to note that most studies are iterative in nature—they often discuss reliability concerns, identify one or more potential solutions, and evaluate the solutions to ensure the reliability target or standard is met. The process of studying the grid has also evolved as lessons from real-world experience have been incorporated and as modeling tools have improved with increased ability to examine variable and inverter-based resources. Historically, most studies have focused on large-scale transmission and generation-based options, but there is increasing recognition of the potential for distributed resources to provide grid services.

1.4 Study Geography

The studies vary across geographical scales, but there are two main types of geographical regions studied: balancing areas and interconnections. In the U.S. power grid, supply and demand are balanced in 66 balancing areas (Figure 1).[9] Therefore, many studies of variability and resource adequacy focus on individual balancing areas. Many studies also examine the potential benefits of improved coordination across multiple balancing areas, including the potential to import and export energy during periods of high system stress or excess renewable production. Balancing areas are electrically interconnected into one of three large, independent grids known as interconnections: Eastern Interconnection (EI), Western Interconnection (WI), and Electric Reliability Council of Texas (ERCOT).[10]

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[7] This is an oversimplified definition of resource adequacy, which includes elements of addressing short-term variability. For additional discussion, see Energy Systems Integration Group (2021).

[8] These models are often referred to as power flow models because one of their main applications is to understand the flow of power along various transmission lines to ensure the lines are not overloaded.

[9] The number and size of balancing areas have changed over time.

[10] The EI and WI includes much of Canada and the WI includes a small part of Mexico.

Figure 1. The U.S. power grid consists of 66 balancing areas and three interconnections (U.S. Department of Energy 2017).

1.5 Studies Considered

Table 1 lists variability and resource adequacy studies that examine annual renewable generation contributions of between 30% and 100% in various regions of the United States that we considered in this review. This table is not intended to be comprehensive and only lists studies that include detailed chronological simulations. Table 2 lists studies that focus on frequency stability.

Table 1. Variability and Resource Adequacy Studies

Region	Cite	Renewable Contribution	Study Focus
WI	GE Energy 2010	35%	Variability
WI	Lew et al. 2013	33%	Variability
EI	Bloom et al. 2016	30%	Variability
EI and WI	Bloom et al. 2022	40%	Variability, Resource Adequacy
North America	Brinkman et al. 2021	70%–80% by 2050	Variability, Resource Adequacy
USA	Mai et al. 2012	80% by 2050	Resource Adequacy, Variability
California	Brinkman et al. 2016	56%	Variability
Los Angeles	Cochran et al. 2021	100% by 2035/2045	Variability, Resource Adequacy
New England	Boughan et al. 2022	95% carbon free	Resource Adequacy
Pacific Northwest	Ming et al. 2019a	60%–100% by 2050	Resource Adequacy
California	Ming et al. 2019b	100% by 2045	Resource Adequacy
California	Douglas et al. 2009	33% by 2020	Variability
PJM	GE 2014	30%	Variability
Midcontinent System Operator	Prabhakar et al. 2021	>50%	Variability
Southwest Power Pool	Southwest Power Pool 2016	60%	Variability
PJM	PJM 2021	50%	Variability, Resource Adequacy
New York	NYISO 2022	70%	Resource Adequacy
New England	Mettetal et al. 2020	60% renewable/ 70% clean	Resource Adequacy, Variability

Table 2. Frequency Stability Studies

Region	Year	Max. Instantaneous Inverter-Based Resource Contribution
WI	Miller and Pajic 2018	~60%
WI	Miller et al. 2014	53%
ERCOT	Miller et al. 2008	~20%
EI	Miller et al. 2013	25%
WI	Gevorgian et al. 2015	80%
WI	Tan et al. 2018	80%

EI, WI, ERCOT	Liu et al. 2018	80%

2 Meeting the Ramp: Lessons From Variability Studies

Early studies of variability introduced several important concepts in power system planning and operation with increased use of renewable energy. One is the concept of net load, or load minus the contribution of renewables. Net load represents the energy that must be served by the balance of the system fleet. Figure 2 illustrates a large increase in net load in the late afternoon that occurs in a system with significant solar contribution.

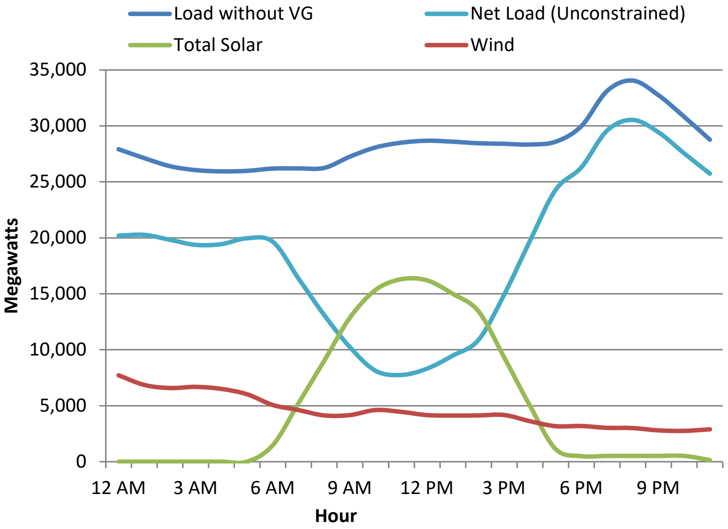

Figure 2. Concept of net load.

VG = variable generation

Another important concept introduced by these early studies is the "flexibility supply curve," which suggests that a variety of options should be considered for the grid to address the increased ramping requirements along with the uncertainty of renewable supply. Wind and solar can then be deployed at the lowest possible cost. Figure 3 shows an example flexibility supply curve; many of these options have been deployed in the past two decades and have helped achieve the levels of renewable deployment to date, discussed in Section 5.

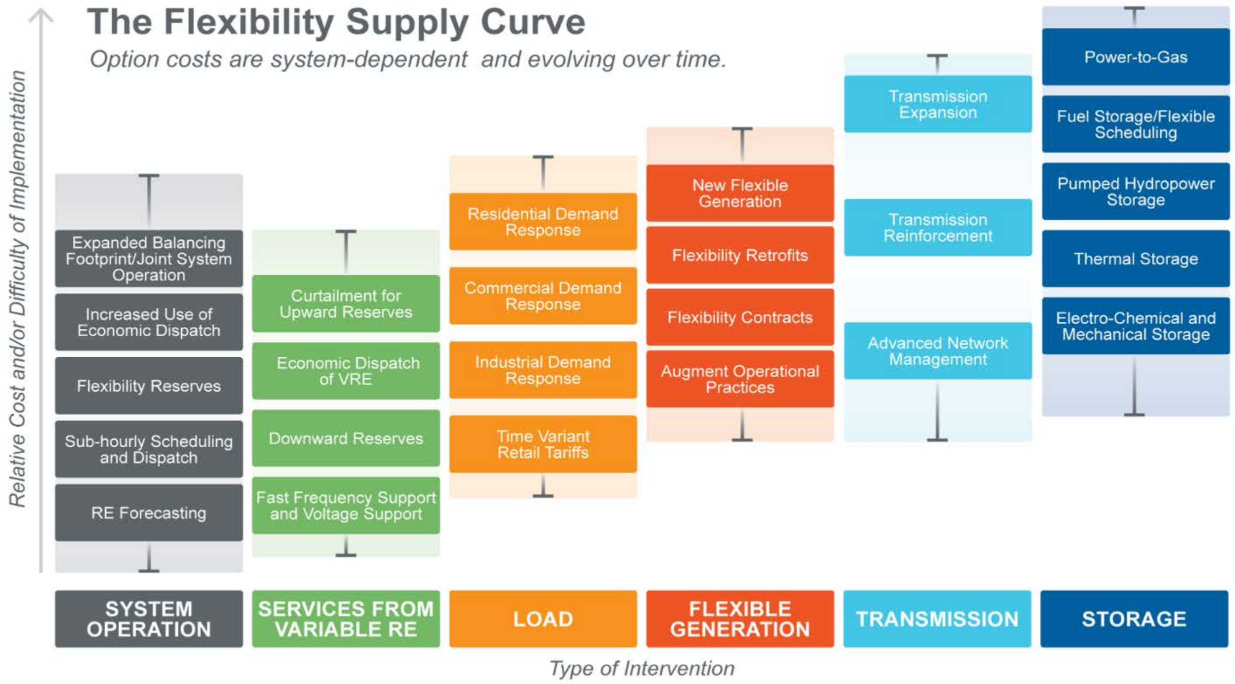

Figure 3. Example of a flexibility supply curve[11]

As an example, early variability studies identified the role of geographic diversity in reducing the variability of renewable resources. While the output of a single, small solar system can change rapidly due to passing clouds, the aggregated output of many, geographically dispersed systems is much smoother and can be better forecasted (Zhang, Hodge, and Florita 2013). Figure 4 shows an example comparing the variability of the solar resource at a single site vs. multiple sites and shows that variability typically occurs over longer timescales (minutes to hours), which reduces the potential need for expensive operating reserves. A similar benefit of aggregation occurs with wind generators.

By balancing supply and demand over larger regions (via improved balancing area coordination or creating larger balancing areas), the variability of renewables (and also of regional loads and other generation resources) is significantly reduced (Denholm and Cochran 2015). System operation costs have therefore been reduced, and the benefits of renewables in offsetting fossil fuel use have increased. Early assumptions about the need for “1:1 spinning backup” from fossil-fueled resources have largely been refuted, and studies (along with real-world experience) have demonstrated that the costs of increased fossil-fuel plant cycling are small compared to the fuel cost savings from reduced fossil fuel use (Lew et al. 2013).

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[11] Note that this chart is intended to illustrate the concept of a supply curve; the order of the individual components is not definitive.

Figure 4. Normalized PV output for increasing aggregation of PV plants in Southern California on a partly cloudy day

Studies have also identified benefits related to improved renewable production forecasting and shorter-term generator scheduling in response to changing conditions. Several regions have introduced flexible ramping reserves specifically to address sub-hourly renewable variability. Flexible ramping reserves provide a lower-cost alternative to addressing solar and wind variability with higher cost regulating reserves, which may have response rates faster than are actually needed (Denholm, Sun, and Mai 2019). Several regions also now allow wind and solar to provide operating reserves, particularly during periods of very high renewable generation when the output of fossil fuel generators is substantially reduced.[12]

As a result of these actions, several regions have met or exceeded the levels of renewable deployment evaluated in the earliest studies, demonstrating the benefits of careful study and planning. Many forward-looking studies examining even greater renewable deployment have identified additional options to address growing variability. These options include greater use of storage and increased use of solar and wind dispatch, where the output of renewable generators is controlled to reduce ramp rates and to provide reserves by operating at partial output in a manner similar to the way in which conventional plants provide reserves.[13] More coordination across larger geographical areas can provide additional benefits—some studies suggest benefits related to coordinating grid operations across much larger regions, and potentially across the interconnections, through expanded transmission capacity.

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[12] This is already common practice in several regions, most notably in Texas (Milligan et al. 2015; Chernyakhovskiy et al. 2019).

[13] 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.

3 Meeting the Demand: Lessons From Resource Adequacy Studies

With the growth in wind and solar deployment and the increase in fossil-fueled generator retirements, more recent studies have shifted focus to resource adequacy. These studies are often in the context of regional renewable and climate goals, and many are focused on renewable contributions greater than 50%. The studies all identified pathways to achieve high levels of renewable contributions while maintaining resource adequacy targets, which often aim for an expected loss of load of less than 0.1 days per year (Electric Power Research Institute 2022). The studies identify several important concepts:

1. 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.

2. Resource adequacy should be considered at all hours of the year, not just during periods of traditional demand peaks.

3. Fossil resources will increasingly transition from acting as energy resources (that run frequently and serve much of the day-to-day demand for electricity) to acting as capacity resources (that run less frequently, mainly during periods of very high demand or low renewable supply).

4. Approaches to maintain resource adequacy vary depending on the level of renewable contribution, decarbonization targets, and how far in the future the study examines.

In most regions, wind and solar are being added to a much larger system, where existing hydropower and thermal plants provide the majority of capacity needed to maintain resource adequacy. As a result, ensuring resource adequacy in the near term means incremental additions are needed to replace retiring capacity or to address load growth. In addition to traditional generation resources, other options to provide resource adequacy include transmission, storage, and demand-side resources.

New approaches must be considered when evaluating the potential resource adequacy contributions of renewable resources. For example, combinations of wind, solar, and storage can contribute to resource adequacy, but unlike thermal and hydropower resources, these contributions depend on the amount of the resources already installed. For example, Figure 5 shows the peak summer load in Texas during two days in 2022, and the impact on net peak load after the contribution of solar energy on this day. In this example, there is a substantial reduction in net demand, reducing the need for fossil-fueled resources to maintain resource adequacy during the summer peak. However, the net load has been shifted to the early evening when solar output has fallen, and doubling the amount of solar (shown by the orange line) would provide no further reduction in net load. This is a significant limiting factor for solar to (by itself) provide resource adequacy in grids with even greater deployment of renewables. At the same time, the change in net load shape also makes it easier for storage to meet the remaining (shorter) summer peaks, demonstrating considerable synergy between the two technologies.

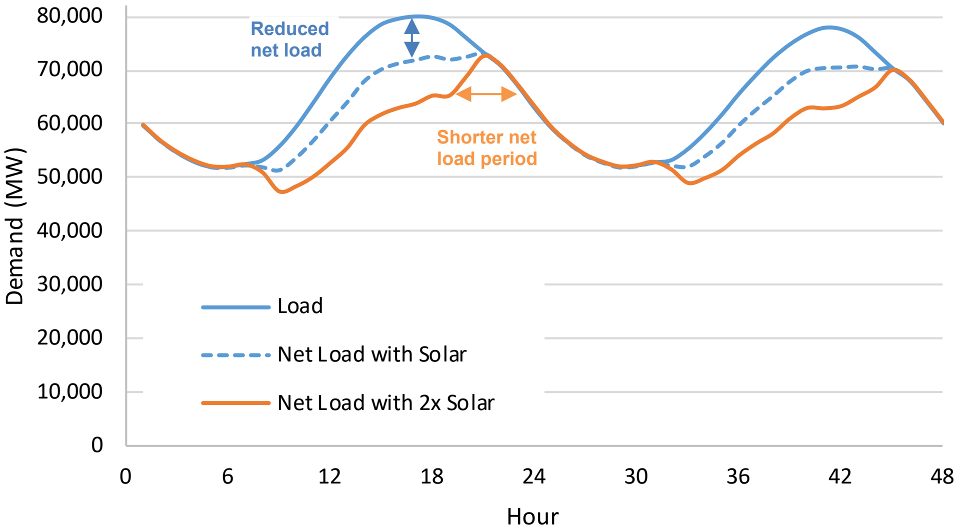

Figure 5. Example of the impact of solar on net load in ERCOT on July 20–21, 2022. The solar already installed has reduced the net load, providing resource adequacy benefits. Additional solar has limited ability to reduced net load but shortens the length of the net load peak, making it easier for shorter-duration energy storage (or demand response) to provide additional resource adequacy benefits.

The role of fossil-fueled resources in high renewable studies varies considerably, depending largely on renewable energy and decarbonization targets. For example, the results from one nationwide grid study in Figure 6 show the energy contribution (top) and contribution toward resource adequacy (bottom) provided by different resources under increasing levels of annual renewable contribution ranging from 57% to 100% (Cole et al. 2021). In many cases, keeping existing (or even building new) fossil-fueled resources is often identified as the least-cost approach to maintaining resource adequacy while transitioning to greater levels of decarbonization. For example, in the case of achieving 57% contribution from renewables, fossil-fueled generation provides about 30% of annual electricity generation (energy) but about 60% of firm capacity. Thus, as the contribution from renewables increases, fossil-fueled generators transition to act primarily as a source of capacity.

There is considerable interest in clean firm technologies that can meet demand during extended periods of lower wind and solar output such as seasonal storage.[14] However, studies have demonstrated that annual contributions of 80% can be achieved without significant deployments of new clean firm technologies by deploying a mix of renewable energy, storage, and potentially significant amounts of existing (or new) fossil-fueled generators. The fossil-fueled generators are maintained in the system primarily to provide resource adequacy (not energy); because they operate infrequently, they produce relatively few emissions. The study shown in Figure 6 does not deploy clean firm technology until annual renewable contribution exceeds 90%, (in part due to the assumption of nationwide coordination of the power grid and large-scale deployment of interregional transmission). This emphasizes the potential to get very deep decarbonization while

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[14] While no technology is truly “firm” (having 100% capacity credit), the term clean firm refers to technologies that are both low emission and have high capacity credit.

maintaining a large amount of fossil-fueled capacity used only during periods of extremely high demand or low wind and solar.

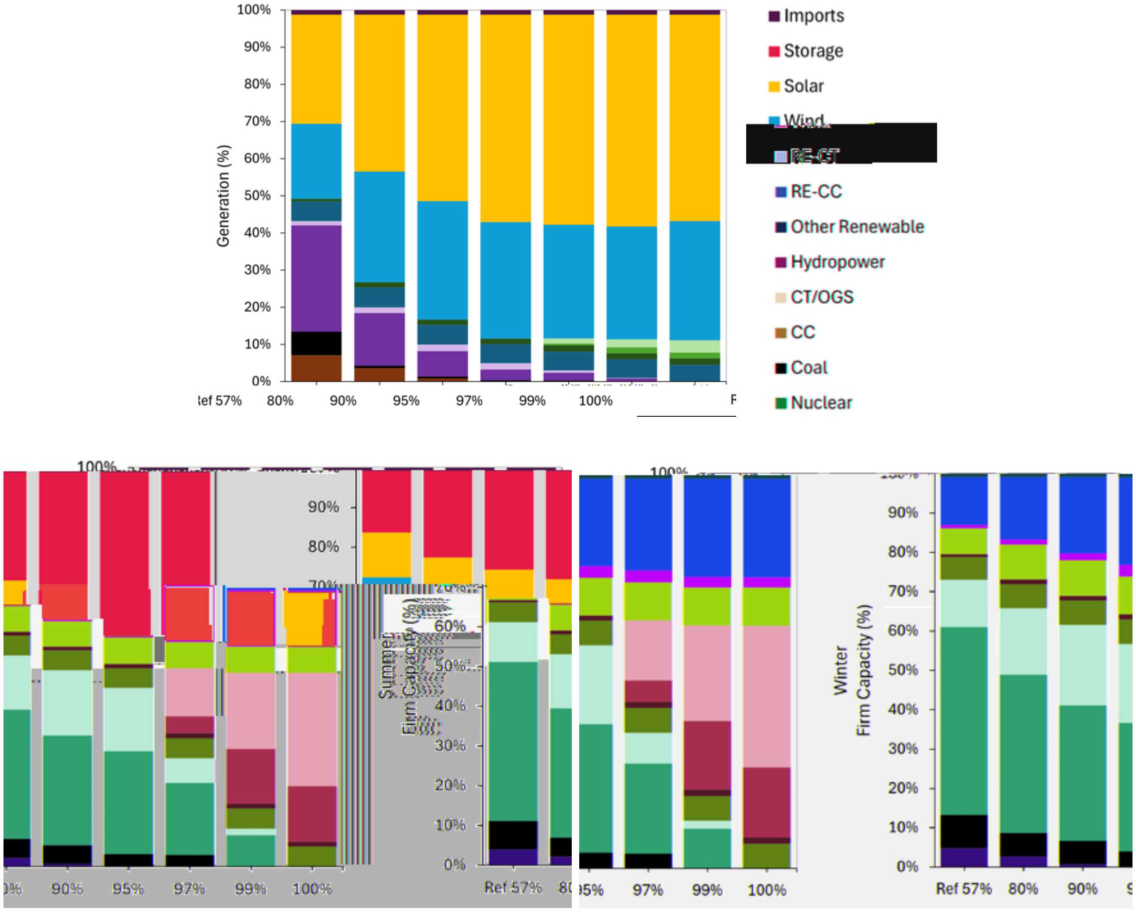

Figure 6. Example of an energy mix (top) and firm capacity (bottom) from one study of the evolution to 100% clean energy, where fossil fuels continue to provide a large amount of capacity but with a decreasing amount of energy (Cole et al. 2021).

There is considerable uncertainty about which technologies might be the most cost-effective to provide the mix of capacity that will likely be required in 100% clean energy systems. They would be required to provide reliable capacity during multiday periods in all seasons. Many of the proposed technologies envisioned in 100% clean energy scenarios (including carbon capture, hydrogen, or next-generation nuclear) have yet to be deployed at scale. Many of these technologies, particularly hydrogen, will require significant changes to infrastructure and are associated with changes to the entire energy system beyond the electricity grid.

4 Keeping the Grid Moving: Lessons From Frequency Stability Studies

4.1 Frequency Stability – Summary of the Issue and Study Approach

Studies to date provide a strong indication that frequency stability can be maintained with understood technologies, including some technologies that have already been deployed at scale. The current grid relies largely on generators that spin at a nearly constant frequency. In the moments following a sudden loss of supply, such as a transmission line outage or generator failure, the supply/demand imbalance can result in a decline in frequency as the system slows down. But some of the inherent stored energy in existing generators (inertia) is injected into the grid automatically after a fault, which keeps the system from slowing down too fast and gives the system time to detect and respond to the loss of supply (Denholm et al. 2020).

Inertia is part of the more general category of "frequency response," which consists of several processes that detect and respond to changes in frequency and prevent frequency from dropping below a minimum level at which the system must initiate controlled blackouts to prevent damage to equipment. Frequency response has historically been provided by synchronous generators in thermal (fossil fuel and nuclear) and hydropower plants.

Wind, solar, and battery storage use power electronics (inverters) to provide grid-compatible electricity and do not behave the same way as synchronous generators. These inverter-based resources (IBRs) do not automatically provide frequency response in the seconds and minutes following a grid event or disturbance. As a result, replacing conventional generation with IBRs can reduce traditional frequency response, including real inertia, and can decrease the stability of the power system if no mitigating actions are taken. This means there is a need to study the impact of IBRs and develop methods to increase their use without compromising frequency stability.

4.2 Study Findings

There are several consistent themes among frequency stability studies to date. They all demonstrate that as IBRs are added, their contribution can lead to synchronous generators being turned off during very windy or sunny periods. This leads to a reduction in physical inertia and inherent frequency response.

Multiple solutions have been identified in these studies to mitigate the decline in physical inertia and maintain sufficient frequency response. The main approach studied is the use of fast frequency response (FFR), which exploits the ability of electronic devices to respond very rapidly to changes in frequency. Fast frequency response is obtained from multiple sources, including flexible loads that are paid to disconnect for very short periods of time or IBRs that can rapidly increase output. Energy storage, wind, and solar can reduce output during periods when there is available energy from wind and solar resources and then rapidly increase output in response to a fault. All of these devices can respond faster than conventional generators; this rapid response significantly decreases the amount of physical inertia required.

The amount of mitigation required depends significantly on the size of the grid, the amount of IBRs deployed, and the makeup of the remaining generation fleet. The need is smallest in large grids that have a large contribution of low-carbon resources that use synchronous generators, including hydropower, nuclear, biomass, and geothermal. Even with significant deployment of IBRs, studies of the EI (serving about 70% of the nation's electricity demand), show that this grid can support extremely large amounts of renewable resources with small impact on frequency stability. The WI is smaller, but also has significant clean synchronous generation, and the need for FFR is relatively small, even with large contribution from IBRs (Denholm et al. 2020). Figure 7 shows an example during a period when IBRs are providing 60% of the WI's entire generation (Gevorgian, Zhang, and Ela 2015). This chart shows the frequency after the worst-case fault the system is expected to address. In cases where no FFR is deployed, the frequency falls below 59.5 Hz, where load shedding must occur. But the addition of FFR from wind generation avoids this large drop in frequency and maintains stable operation during a worst-case scenario.

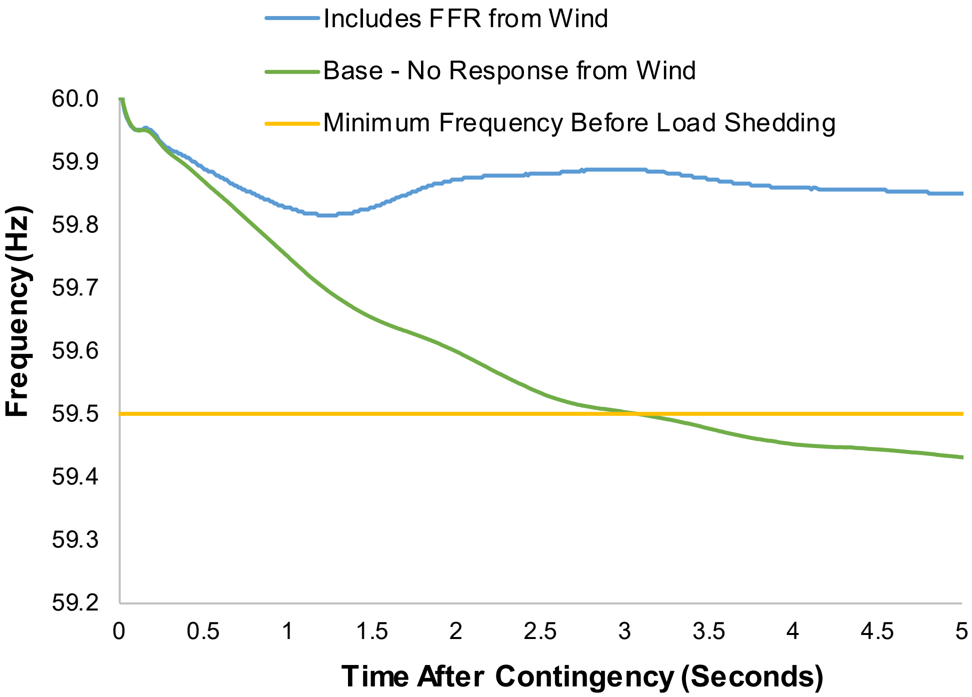

Figure 7. Example of a study demonstrating the benefit of fast frequency response from wind in a grid with decreased inertia (Gevorgian, Zhang, and Ela 2015).

The need to address the decline in inertia is greatest in the smallest of the three grids (ERCOT), which does not have significant hydropower, geothermal, or biomass combustion.[15] ERCOT has already made changes to system operation, including using FFR, largely from loads. ERCOT has also required IBRs to provide frequency response services.

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[15] Additionally, ERCOT has a contingency size that is about the same as that of the WI, which increases the need for frequency response.

IBRs are increasingly required by state and federal standards to provide grid services such as frequency response (FERC 2018). In addition to FFR, there are additional well-proven approaches that maintain physical inertia such as using clean energy resources that use synchronous renewable generators, or stand-alone devices that provide physical inertia without requiring a generator (synchronous condensers).

Finally, it is possible to operate grids without large amounts of physical inertia by using grid-forming inverters.[16] These devices have been deployed in smaller grids, but there have been limited studies of the potential use of these devices at the interconnection level, which is required to study system frequency stability.

Overall, multiple studies indicate that the use of measures such as FFR can mitigate the loss of synchronous generation due to the variable generation that will likely be deployed in the coming decade, especially in the larger EI and WI grids that serve more than 90% of the country. The biggest outstanding question is which combination of solutions might achieve the lowest cost.[17]

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[16] While current inverters (known as grid-following inverters) can provide frequency response, they cannot inherently and independently create the alternating current waveform the grid uses as a reference. This is one of the main distinctions between these and grid-forming inverters, which create the waveform.

[17] There are a number of other reliability issues related to large-scale IBR deployment beyond frequency that are not discussed here. Many are discussed by NERC (2023).

5 From Study to Practice: Where Are We Now and Where Are We Going?

While the U.S. power grid is well below 100% variable renewable energy on average, several regions in the country (and many around the world) have achieved very high contributions from renewable energy over shorter timescales. Figure 8 illustrates the average and maximum hourly contribution from wind and solar resources for several regions in 2023. The data in Figure 8 do not include the contribution of rooftop or other behind-the-meter (BTM) solar or other renewable or clean electricity resources; however, they demonstrate the ability of the system to remain reliable while addressing both variable supply and (in the case of ERCOT) high levels of IBR contributions.

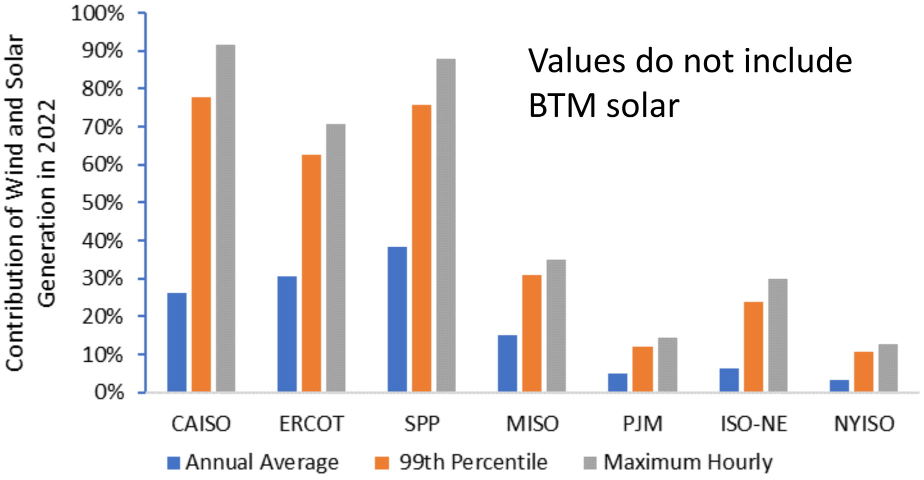

Figure 8. Average and maximum hourly contribution of wind and solar resources in 2023[18]

5.1 Incorporating High Levels of Variable Generation in Utility Planning

The lessons learned from studies and real-world experience is now being incorporated into utility planning for future growth in renewable energy. With wind and solar providing the lowest-cost source of new electricity, and with storage providing cost-effective peaking capacity, many utility resource plans include significant deployment of these technologies. Utility plans account for the low cost of energy from wind and solar, the limits of wind and solar to provide energy during peak periods, and the need to address the variability and uncertainty of these resources—it is well understood that 1 MW of variable generation capacity does not generally provide the same resource adequacy value as 1 MW of retiring fossil-fueled capacity.

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[18] Data provided by Dev Millstein, available at https://emp.lbl.gov/renewables-and-wholesale-electricity-prices-rewep. It should be noted that all regions except ERCOT are interconnected to other grids which mitigates some of the challenges, and there are often other generation resources in these regions that are operating and exporting energy.

Recent resource plans filed to regulatory agencies reflect the expectations that wind and solar can be part of the least-cost mix of resources while maintaining reliable electricity. These plans indicate corporate intentions to deploy the proposed generation capacity and the proposed mix of resources to meet reliability standards required by state and regional regulatory agencies. Table 3 lists five filed resource plans that achieve significant contribution of renewable energy while explicitly stating that the systems are expected to maintain reliability standards.

Table 3. Utility Resource Plans Demonstrating the Mainstream Nature of High Renewable Energy Contribution in Plans That Include Reliability Standards

Utility and Integrated Resource Plan Year (including link to study)	% Renewable Energy	Notable Reliability-Related Findings
Southern California Edison (2022)	90% by 2035, 95% by 2040	"Portfolio passes both the 1-in-10 LOLE reliability assessment and the feasibility and operability (emissions) check in PCM"[a]
Puget Sound Energy (2023)	85% by 2030, 100% by 2045	Scenarios satisfy PRM and include additional capacity for 5% LOLP [a]
Appalachian Power Company (2022)	53% by 2036, 100% by 2050	Scenarios achieve "reliability/reserve margin requirements as set forth by PJM"
Public Service Co of Colorado (2022)	83% by 2028	The plan "meets resource adequacy needs"
Indiana Michigan Power (2021)	~50%–55% by 2041	"The Preferred Portfolio includes additions that when added to the Company's current resources, … ensure the reliable supply of electricity while also maintaining PJM capacity requirements and supporting resource adequacy."

[a] LOLE = loss of load expectation; PCM = production cost model; LOLP = loss of load probability

6 Conclusions

Over the past two decades, dozens of studies have been conducted to evaluate questions associated with maintaining reliability in power systems with an increased deployment of variable renewable energy (wind and solar). These studies have identified approaches to cost-effectively address the variability and uncertainty of solar and wind resources. Many of these approaches have been implemented, enabling a growing contribution of variable renewable energy resources in today's grid. These studies also identify pathways to accommodate future growth, including addressing the changing role of traditional generators from energy resources to capacity resources. Studies have also identified how new technologies can help maintain grid stability. These lessons can support current utility plans to develop large amounts of economic renewable energy deployments while maintaining state and federal reliability standards.

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