GRID RELIABILITY IN THE CLEAN ENERGY TRANSITION

A Primer for Policymakers

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EXECUTIVE SUMMARY

In the summer of 2024, one of the largest regional grid operators in the United States, PJM Interconnection (PJM), faced a significant challenge—outdated and expensive fossil resources were starting to retire, and new resources were not coming online fast enough to meet spiking demand for electricity. These dynamics came to the fore in the 2024 annual auction for capacity resources.

Across its multistate service territory, PJM's primary role is to maintain a reliable grid, which means balancing ever-changing electricity supply and demand down to the minute. PJM's approaches are designed to meet this goal, while also minimizing the costs to electricity customers. Yet due to the mismatch between retirements and new generation, PJM's 2024 capacity auction, which procures resources to meet the highest forecasted electricity demand, resulted in prices nearly ten times higher than the year prior.[1] These high prices will result in $14.7 billion in capacity payments made by customers across PJM's service territory as a part of their electricity rates. PJM's multi-billion-dollar conundrum is shared by utilities and grid operators across the country: how are we going to meet growing demand for electricity, maintain a reliable grid, and manage the transition to new clean energy resources in a cost-effective way?

Abundant, reliable, and affordable electricity is central to economic prosperity, energy security, public health, safety, and comfort. In the U.S. and around the world, electric grids are undergoing transitions driven by myriad factors. But electric utilities are now facing increasing demand from data centers, manufacturing, and cryptocurrency mining, as well as electric vehicles (EVs), industrial equipment, buildings, and appliances. A rapidly changing climate and more extreme weather-related events are placing unprecedented strains on all systems, including aging electric grid infrastructure—70 percent of transmission lines and power transformers are 30 years or older.[2]

Fortunately, policies, regulations, consumer demand, and favorable economics have been accelerating the deployment of carbon-free, clean electricity generation, including wind, solar, and battery storage for over a quarter century.

Throughout the transition, ensuring a reliable and resilient electricity grid remains a top priority. The resources to maintain a reliable grid are available—for example, over 2600 gigawatts of new clean projects are waiting to connect to the U.S. grid. That amount of new generation is nearly double the grid's current capacity.

As the grid continues to evolve, it is time to update the way we think about and approach grid reliability. Utilities and grid operators need to build and interconnect new generation faster and more efficiently, while simultaneously deploying strategic demand-side solutions at scale. While the task may seem daunting or infeasible to some, the power system is no stranger to evolution. In the early 2000s, a combination of cheap natural gas due to the shale boom, advancements in gas turbine technology, and environmental regulations led to a rapid shift from coal to natural gas power.[3] From 2007 to 2023, the share of coal generation within total U.S. electricity production declined from 50 percent to 16 percent, gas generation nearly doubled from 21 percent to 43 percent, and wind and solar grew from less than 1 percent to 15 percent.[4]

Continuing cost declines in wind and solar have made them the cheapest new electricity resources,[5] and cost reductions for utility-scale battery storage technologies have exceeded forecasts year-over-year—in 2024, the amount of battery storage installed nationwide doubled.[6] That same year, wind, solar, and batteries made up 93 percent of the new electricity resources added to the grid.[7]

Yet grid operators, reliability authorities, and utilities are ringing reliability alarm bells,[8] and outdated views on grid reliability are colliding with slow-moving institutions.

Thankfully, there are proven methods for enhancing grid reliability while adding new clean energy resources and tapping into demand-side resources. Regions around the world are already proving that grids operating on high penetrations of carbon-free renewable energy stay reliable. For instance, large grids in the Midwest, Texas, and California regularly operate using more than 70 percent renewable energy,[9] and individual states run on much higher percentages of renewables than the country as a whole—Iowa and South Dakota generated roughly 60 percent of all their electricity in 2023 from wind power.[10] In Hawaii, South Australia, and Denmark, grids are already operating using 100 percent renewable power for days at a time.[11] Notably, though, these jurisdictions have adjusted their planning and operating practices to integrate higher penetrations of renewable energy and battery storage without compromising reliability.

But the technical aspects of grid reliability are often daunting to navigate for those not involved in day-to-day grid operations. Policymakers and regulators tasked with ensuring a reliable grid and utilities operating the electric grids within their jurisdiction may shy away from asking tougher questions that dig into the real risks of outages, safety issues, or cost overruns. Grounding reliability discussions in meaningful solutions requires a bridge between the world of utilities and grid operators and those who regulate their businesses and oversee their operations.

This report seeks to provide such a bridge. We offer here an accessible primer on the basics of planning and operating a reliable grid in the context of the clean energy transition—reducing damaging climate emissions and electrifying industry, vehicles, and buildings. This report will demystify how clean energy resources can provide reliability services, while also discussing the challenges in achieving a 100 percent clean electricity grid. We offer targeted recommendations for policymakers, regulators, utility planners, and grid operators that can speed the addition of clean energy resources, while ensuring reliability and affordability.

Each chapter of this report focuses on a primary element of grid reliability, highlighting relevant research, data, and insights from experts in grid reliability:

Chapter 1: Managing grid reliability in a changing world defines key reliability terms and highlights the importance of moving beyond a reliability construct that depends primarily on baseload power to one that depends on a broad portfolio of resources and load flexibility. This broad portfolio also leverages supply, demand, and storage assets using strategic management methods.

Chapter 2: Resource adequacy and energy storage discusses evolving approaches to resource adequacy, including changes to planning processes to incorporate new types of resources. It highlights the need to move beyond planning reserve margins to incorporate weather-dependency and energy limitations in a system that relies on large amounts of energy storage.

Chapter 3: Real-time, reliable operation of a diverse portfolio discusses the resource attributes needed to keep the grid functioning in real time, including voltage stability, frequency regulation, and inertia, as well as how a diversity of resources and new technologies contribute to a reliable grid.

Chapter 4: Demand-side solutions highlights the value of flexible, responsive demand in a time of load growth and identifies strategies to optimize deployment of demand- and supply-side resources in concert.

Chapter 5: Clean firm energy resources defines clean firm energy and discusses the development stage of various technologies and their importance to reducing emissions.

The **Appendix** provides a quick reference alphabetized guide to key terms to help readers navigate some of the more technical concepts of grid reliability.

This report is not intended to be a comprehensive treatise on grid reliability but instead serve as a synthesis of research and real-world experiences that can inform solutions to the challenges facing the electricity grid today. With this report in hand as a reference, policymakers should gain confidence that a high-renewable, dynamic, and increasingly carbon-free electricity system can keep the lights on and be more resilient in the face of extreme weather, even as demand for electricity grows. In each chapter, we offer targeted recommendations that decision-makers can employ to support the evolution of the grid while enhancing reliability, affordability, and security.

A summary of our recommendations and takeaways for each chapter is available in a separate document at https://energyinnovation.org/wp-content/uploads/Grid-Reliability-in-the-Clean-Energy-Transition-Key-Takeaways.pdf.

CHAPTER 1: MANAGING GRID RELIABILITY IN A CHANGING WORLD

Summers and winters are introducing new grid reliability risks in the form of extreme heat and cold, both exacerbated by the climate crisis.[12] Heat waves cause people and businesses to crank their air conditioners for relief, spiking electricity demand and adding stress to the grid, while overheated lines and dry foliage can cause wildfires. Winter storms and polar vortexes, such as Elliott and Uri, strain aging infrastructure and lead to deadly conditions, especially for those living in poorly insulated homes.

At the same time, electricity is getting cleaner—in 2023, the U.S. generated 40 percent of its electricity from carbon-free sources.[13] Fifteen percent was generated from wind and solar energy, both of which are now the cheapest sources of electricity, and the fastest growing. The other 25 percent from carbon-free sources came from nuclear energy, hydroelectric energy, and geothermal energy.

To help prepare the nation's electric utilities and grid operators for the summer and winter seasons ahead, the North American Electric Reliability Corporation (NERC)[14]—the multinational nonprofit regulatory authority whose mission is to assure the effective and efficient reduction of risks to the reliability and security of the North American grids—releases annual summer and winter reliability assessments.[15][16]

NERC's reports assess the U.S.'s and Canada's ability to meet expected seasonal electricity demand, including an evaluation of the risks associated with wildfires (which impact the physical grid infrastructure) and drought (which impacts hydroelectric and nuclear facilities), and provide short-term recommendations on how to overcome any potential shortfalls.

NERC's 2023-2024 findings highlight that while electricity supply is sufficient across the country under normal conditions, several regions are at risk for supply shortfalls during extreme heat and cold.[17] NERC cited the retirement of aging and expensive fossil fuel power plants as a factor in this dynamic but also found that "increased and rapid deployment of wind, solar, and batteries make a positive difference," highlighting that one of the most important tools bolstering reliability is adding new, clean generation capacity.[18] Winter reliability risks, on the other hand, are primarily based on the performance of gas fired-power plants and availability of fuel supply. As we move toward a cleaner electricity system, reliability is front of mind for policymakers, utilities, system operators, and electricity consumers alike, and for good reason—lives depend on the power staying on.

THE NUTS AND BOLTS OF RELIABILITY

It's helpful to understand the basics of electricity reliability—a term used often, but not always consistently. There are three separate but interconnected pieces to ensuring that power from the grid is reliable, as depicted in Figure 1.

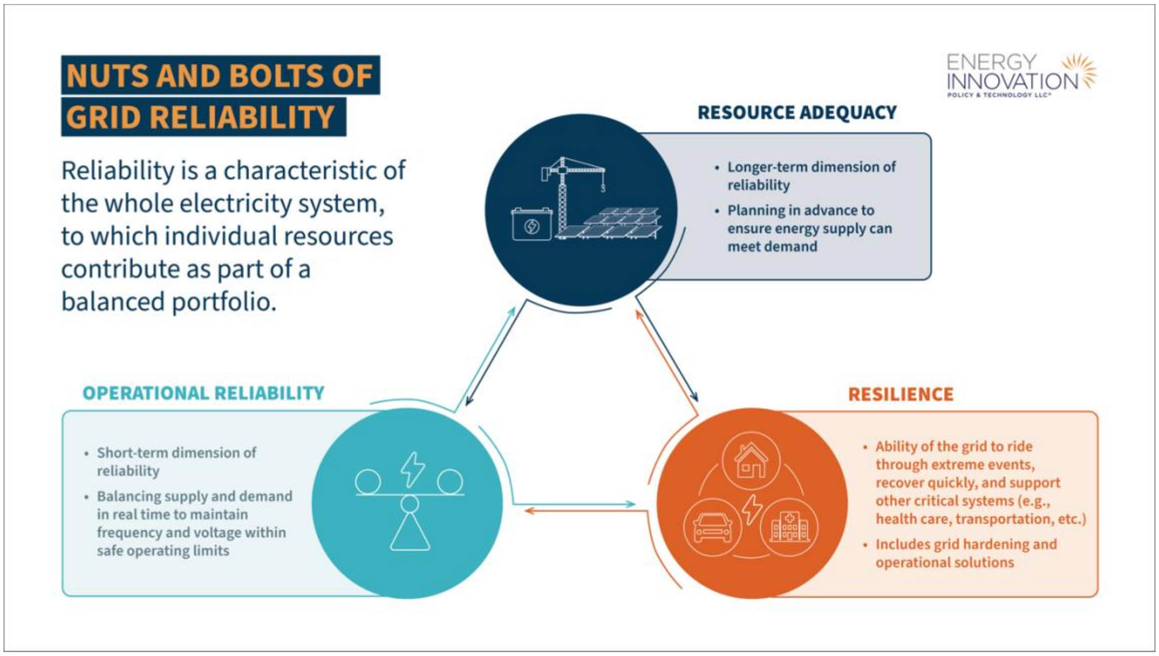
First is *resource adequacy*, which means having enough energy to meet demand—either in the form of supply-side generation or demand-side distributed resources. Resource adequacy is a longer-term dimension of reliability that requires analysis and planning to estimate long-term demands and design and implement measures that deliver sufficient new resources to serve those demands.

Second is *operational reliability* of the grid, which refers to balancing energy supply and demand in real time to maintain frequency and voltage within safe operating limits. Operational reliability is a short-term dimension that requires ongoing monitoring and control of the entire grid, and extensive efforts to design and implement markets, operational rules and systems, and infrastructure to support day-to-day grid operations.

Third is *resilience*, which is the ability of the electricity grid to ride through extreme events, recover quickly, and support other connected systems, such as transportation, health care, and public safety. Connected to resilience is grid hardening, which refers to a myriad of technology and operational solutions that help the grid withstand these major events without disruption.

Reliability is a characteristic of the whole electricity system, to which individual resources contribute. Every source of electricity has different characteristics that should complement each other in a balanced portfolio. With respect to resource adequacy, no resource is available 100 percent of the time. For example, solar and wind output vary with weather conditions over the course of the day and year. Large-scale nuclear plants are built to provide consistent power but are difficult to ramp up or down to adjust supply when needed. Gas and coal plants are typically considered "dispatchable" or available on demand, but can suffer outages, particularly in extreme weather events as seen during recent Winter Storms Uri and Elliott.[19,20] Fossil and nuclear plants also require planned outages for routine maintenance and refueling. Batteries help moderate variable output, and transmission and distribution (T&D) lines enable sharing surplus resources while serving as the backbone of the grid. Maintaining a reliable grid requires valuing every resource's contribution accurately and building a generation portfolio that balances supply and demand 24/7.

Figure 1. The Nuts and Bolts of Grid Reliability



When electricity supply and demand are matched, electricity will flow through the grid at a constant frequency and voltage. But as supply and demand vary throughout the day, frequency and voltage can begin to fluctuate. Grid services are the contributions that operators call up from different resources to keep the grid in balance.[21] These services include frequency response, voltage regulation, and more. Historically, the inertia from spinning turbines powered by gas, coal, and nuclear helped stabilize grid frequency. Today, however, changing economics and regulations have pushed more conventional fossil resources to retire, so grid operators are already using renewables, storage, and demand-side resources to provide grid services. The relative ability of wind, solar, batteries and associated power electronics to provide grid services compared to that of spinning turbines is detailed in the Figure 2 below from Milligan Grid Solutions.[22]

Figure 2. Grid services provided by inverter-based and synchronous resources

	Inverter-Based			Synchronous				Demand Response
	Wind	Solar PV	Storage/ Battery	Hydro	Natural Gas	Coal	Nuclear	Demand Response
Disturbance ride-through	Excellent	Very Good	Very Good	Excellent	Good	Good	Good	Good
Reactive and Voltage Support	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Excellent	Limited
Slow and arrest frequency decline (arresting period)	Very Good	Very Good	Very Good	Very Good	Good	Good	Limited	Good
Stabilize frequency (rebound period)	Very Good	Very Good	Very Good	Very Good	Excellent	Limited	Limited	Good
Restore frequency (recovery period)	Good	Good	Good	Excellent	Excellent	Limited	Incapable	Good
Frequency Regulation (AGC)	Very Good	Very Good	Excellent	Excellent	Excellent	Limited	Incapable	Excellent
Dispatchability/Flexibility	Good	Good	Excellent	Excellent	Very Good	Limited	Incapable	Good

These services also contribute to frequency restoration, but are also considered essential reliability services on their own. (Frequency Regulation (AGC); Dispatchability/Flexibility)

Excellent · Very Good · Good · Limited · Incapable

Source: Milligan Grid Solutions.

Numerous entities share responsibility for the reliable operation of the electric grid, including the Federal Energy Regulatory Commission (FERC), NERC, grid operators (including regional transmission organizations (RTOs) and independent system operators (ISOs)), state utility regulators, and electricity providers. FERC oversees the reliability of the bulk power system and delegates the development and enforcement of standards to NERC but is responsible for approving these standards. FERC also approves rates related to wholesale sale of electricity and transmission in interstate commerce. NERC assesses national and regional resource adequacy, sets operational reliability standards, monitors compliance with those standards, and can penalize non-compliant reliability authorities. RTOs and ISOs use market mechanisms to provide reliability in grid operations and ensure that transmission and generation capacity is available. State utility regulators evaluate utility resource plans, assess the reliability and quality of utility service, and oversee the prudency of grid-related investments for regulated public utilities. Electricity providers plan their future resource mix; make investments in new generation, transmission, and distribution infrastructure to meet demand; and, in the parts of the West and Southeast, operate their bulk power systems. Grid operators are responsible for maintaining the reliable and secure operation of the electrical grid. They constantly monitor the grid's performance, ensuring it operates within its capacity while always meeting electricity demand.[23]

CHANGING RELIABILITY CONSIDERATIONS WITH THE ENERGY TRANSITION

The grid is undeniably in transition. The shift to clean electricity and more electrified end uses has been accelerating over the past twenty-five years. Rapid cost reductions and significant cost advantages of solar and storage relative to traditional fossil resources are primary drivers of this shift. Federal policy and incentives,[24] state clean energy goals,[25] policy and regulatory changes, customer preferences for clean energy, and utility[26] and business leadership are paving the way.[27]

In 2024, wind, solar, and batteries accounted for 97 percent of new utility-scale generating capacity, while new natural gas capacity made up only 2.5 percent.[28] Battery storage has also seen a meteoric rise with the addition of 15 GW of battery storage in 2024 alone—a near doubling of storage capacity nationwide.[29] This fast-growing addition of renewables and storage is welcome as electricity demand increases and uneconomic fossil fuel plants retire. Other demand-side resources and operational changes are also in the toolbox as grid operators work quickly to manage the transition without impacting grid reliability, safety, and affordability.

The growth of clean energy resources introduces new concerns about how to plan and operate a reliable grid integrating these new technologies. Wind and solar are different from fuel-based resources in several important ways. First, their energy production is dependent on the weather, which means it is variable but mostly predictable. Second, their output is controllable and highly responsive to digital signals, but they do not possess the large, spinning mass of fossil fuel plants. Third, renewable energy projects tend to be smaller on average than fossil fuel plants, meaning that more individual projects are needed to generate the same electricity. These changes are significant, but manageable if grid operators are willing to embrace new technologies.

"We know that we need a portfolio of resources on the grid that, working together, can provide resource adeqaucy, or energy when we need it, but that portfolio does not necessarily need to include baseload or 24/7 resources." – Ric O'Connell, Executive Director GridLab

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Ric O'Connell, Executive Director of GridLab, says that one of the biggest misconceptions in the energy transition is the continued need for baseload power, or plants that are expensive to build but historically cheap to operate and therefore run almost all the time. O'Connell explains that "we know we need a portfolio of resources on the grid that, working together, can provide resource adequacy, or energy when we need it, but that portfolio does not necessarily need to include baseload or 24/7 resources."

While the shift to this new paradigm presents challenges, we are gaining confidence in the reliability of a clean grid. Previously there was "trepidation about even adding small amounts of weather-dependent power sources like wind and solar to the grid," said O'Connell. "Now, large, sophisticated grids in the Midwest, Texas, and California regularly run on a 70 percent or higher share of wind and solar for hours at a time."[30,31] We have proven examples of smaller grids running at even higher percentages of weather-dependent resources—the island of Kauai has been able to run on 100 percent renewable energy for at least nine hours at a time.[32] Multiple studies show that the U.S. grid can run on up to 80 percent clean electricity with technology available today.[33]

> *"Reliability disucssions will lead to the more cost-effective solutions if they start with the data-driven analytical work required to understand and quantify the problem that we are aiming to solve."*
> *– Allison Clements, former FERC Commissioner*

To build this portfolio, utilities, regulators, and grid operators will need to be able to accurately evaluate each resource's contribution to resource adequacy and operational reliability. As former FERC Commissioner Allison Clements said, "reliability discussions will lead to the more cost-effective solutions if they start with the data-driven analytical work required to understand and quantify the problem that we are aiming to solve."[34]

RELIABILITY AND POLICY

While the grid shifts from a still fossil-heavy system to one that is powered by clean, carbon-free electricity generation, we must answer three questions:

1. Can a clean grid offer the same or better reliability compared to the more fossil fuel intensive grid of the past?
2. Can the grid be reliable as we are transitioning?
3. Can a clean grid meet the demand from more electrified end uses without compromising reliability?

The answer to these questions is "yes," but not without the thoughtful planning and policies in place.

To maintain reliability and smooth the transition, policymakers will need to remove barriers to building new, clean resources and connecting them to the grid.[35] With nearly double the current U.S. generating capacity just waiting in interconnection queues across the country,[36] new transmission lines are one of the "biggest barriers to adding sufficient new clean energy," according to O'Connell, and "policy plays a critical role in how we plan, permit, and pay for transmission. Good policy means we can get the transmission built in the time frame we need, so clean energy can come online and maintain reliability." Distribution system upgrades needed to support more electrified end uses, such as heat pumps and EVs, can also be hindered by regulatory and utility processes if they aren't anticipated. And a clean, reliable grid capable of supporting mutual goals of decarbonization and electrification is possible, but it won't happen on its own. It requires changes to how we think about reliability in the context of a changing world and a changing climate.

CHAPTER 2: RESOURCE ADEQUACY AND ENERGY STORAGE

In 2024, coal and gas represented over 90 percent of plant retirements in the U.S. With another 10.9 GW of coal generation capacity expected to retire in 2025, the replacement of these plants with new resources is top of mind for grid operators.[37] Fortunately, new resources are coming online to replace this capacity. Notably, 56 GW of new capacity was added in 2024 across the U.S., with solar, battery storage, and wind constituting 93 percent and natural gas making up 4 percent.[38]

With this shift from fossil plants to clean resources, some electric power industry representatives are raising concerns about resource adequacy (i.e., whether there are enough generation resources to supply energy and capacity to meet rising demand). It is helpful to clarify what resource adequacy means. Technically, resource adequacy means having enough electricity supply and storage resources to meet customer demand, which are highest at peak periods such as hot August afternoons and cold winter mornings. In addition to adding supply, resource adequacy can be achieved by managing demand (for more detail, see Chapter 4). While resource adequacy has been traditionally defined as having enough supply to cover demand, it can be better understood as being able to plan, deploy, manage, and coordinate supply, storage, and demand to assure reliable operations under a variety of conditions and challenges.

Two sets of questions underpin concerns about maintaining resource adequacy through the clean energy transition.

1. **Is it technically feasible to ensure resource adequacy with clean energy resources?** And if so, how might the methods of measuring and planning for resource adequacy need to change to account for the future resource mix? How can demand-side resources best enhance resource adequacy?

2. **Is it practically feasible to bring enough supply and storage resources online fast enough to replace those that are projected to retire?** How do policies, or the absence thereof, help or hinder the development of needed resources?

The answer to each of these primary questions (in bold) is yes—if policies enable a managed transition that balances retirement of the old with installation of the new and encourages creative and strategic grid and utility operations.

WE CAN REACH 80 TO 90 PERCENT CLEAN ELECTRICITY WITH TODAY'S TECHNOLOGIES

Researchers have explored deep decarbonization scenarios via detailed power system simulations and agree that the U.S. can achieve up to 90 percent clean electricity generation using existing technologies. For example, a team from the University of California, Berkeley, Energy Innovation, and GridLab in their 2035 Report 2.0 found that a 90 percent clean grid could meet demand at all hours of the year through the addition of existing energy technologies like solar, wind, and batteries.[39] They also found that no new coal or gas plants would need to be built, even with increased demand from the high electrification of transportation, buildings, and some industry.

The *Net Zero America* study similarly finds that clean sources of energy can supply 70 to 85 percent of U.S. electricity by 2030.[40] This analysis assumes the electricity mix is largely wind and solar, with hydro and nuclear remaining relatively constant while gas usage decreases by about 25 percent and coal generation goes to zero. National Renewable Energy Laboratory research agrees, finding that 71 to 90 percent of electricity could come from clean sources by 2030, again all with existing energy technologies.[41]

Regional studies support the same conclusion, with GridLab and Telos Energy finding that California could reach 85 percent clean electricity by 2030 while maintaining resource adequacy with the addition of primarily wind, solar, and batteries. Here, the use of a diverse set of clean resources, including offshore wind and geothermal, significantly decreases the necessary deployment rate to meet the 85 percent clean threshold.

All of these studies acknowledge that existing gas plants will be an integral part of the power system for the foreseeable future. However, their role will shift increasingly toward use as capacity resources for reliability during higher-risk periods, while their total annual energy contributions are expected to drop significantly.

While research has been done on the pathway from 90 percent or 95 percent to 100 percent clean electricity, these studies tend to rely on technologies not yet widely commercialized, such as carbon capture and sequestration (CCS) or advanced nuclear. Fortunately, we have time for technologies and grid operations to evolve to meet the last 5 to 10 percent of a 100 percent carbon-free electricity grid. Keeping the lights on using primarily wind, solar, and batteries may be possible at these higher percentages, though modeled costs tend to be prohibitively high without the incorporation of dispatchable clean resources or significant flexible demand. Energy efficiency and demand-side measures to lower and manage demand will buy more time and reduce grid risk as new technologies mature and are built and integrated into the grid (see Chapter 4 for more discussion on these demand-side solutions).

For example, the "Moonshot study" by GridLab,[42] which uses the Public Service Company of New Mexico as a case study, finds that there are several viable supply-side pathways to 100 percent clean electricity. These pathways include increasing regional coordination, upsizing wind and solar resources, and would couple CCS with possible future technologies including multi-day energy storage and dispatchable clean sources like geothermal, nuclear, hydrogen combustion turbines, or thermal resources.[43] Priya Sreedharan, program director at GridLab and an author of the Moonshot study, highlights the importance of not letting uncertainty in this final stage delay action on building a lot of clean energy now, saying, "It's okay that we don't know exactly what the last 10 to 20 percent will be. The focus needs to be on building the stuff we know we need and not get hung up on what that perfect clean firm resource is."

"It's okay that we don't know exactly what the last 10 to 20 percent [clean] will be. The focus now needs to be on building the stuff we know we need and not get hung up on what that perfect clean firm resource is." – Priya Sreedharan, Senior Program Director, GridLab

Research shows that mature technologies can get us cost-effectively to high shares of clean electricity, and there are viable pathways to 100 percent clean. However, to plan for a resource-adequate system using clean energy, some changes are needed.[44] While it may be technically feasible to achieve high shares of clean energy in the electricity system, inadequate policies and market rules could stifle the development of resources needed for a reliable grid.

RESOURCE ADEQUACY PLANNING SHOULD ADAPT FOR WEATHER-DEPENDENT, ENERGY-LIMITED SYSTEMS

Resource adequacy is more complicated in a high-renewables world, but grid planners can take several actions to adapt, including consistently accounting for the capacity value of each resource type via a process known as capacity accreditation. This takes into consideration the interdependent nature of clean resources and updating planning practices for changing risks.

First, while critics continually highlight that wind and solar energy are weather dependent and have a variable energy output, many do not apply the same scrutiny to fossil fuel resources and consider them to be always available. This is one of the biggest pitfalls in resource adequacy planning, and one that has had particularly serious implications during extreme weather. Experience over the past decade has shown repeatedly that gas, coal, and nuclear plants are also weather dependent, with a number of these plants failing to perform especially during severe cold temperatures.

Derek Stenclik, founder of the independent modeling firm Telos Energy and lead author of a recent Energy Systems Integration Group paper on future resource adequacy, emphasizes that “there is no such thing as perfect capacity. We need to recognize that all resources have challenges in meeting reliability needs.”[45] As Stenclik observes, the impression that there is a type of electricity generator that can be considered “firm,” or available to be dispatched at any time, is a widespread myth.[46] For example, during Winter Storm Uri, un-winterized gas plants across the state of Texas failed simultaneously, making up 58 percent of the unplanned outages.[47] During Winter Storm Elliott, it was nearly the same story, with 70 percent of the unexpected outages coming from gas plants.[48] Weather-related correlated outages will continue to be an issue as power systems add renewables, so ensuring all power plants are held to the same standard is imperative.[49]

“There is no such thing as perfect capacity. We need to recognize that all resources have challenges in meeting reliability needs."
– Derek Stenclik, Founder, Telos Energy

Second, in a clean electricity future, the reliability value of each resource becomes increasingly dependent on the others. To perfectly determine each resource’s value requires complex calculations that evaluate the relationship between each resource and the portfolio as a whole, a process known as capacity accreditation. However, transparency and certainty on future capacity accreditation values[i] is important for those trying to bring new resources online. Sometimes, says Sreedharan, we will have to “accept that none of these methods will be perfect” in accrediting these resources to keep markets accessible and resources coming online quickly.

Third, resource adequacy analysis has long been determined by predicting the time of day or year in which peak electricity demand occurs, and then planning to have enough generation capacity available, plus an additional margin of around 15 percent to account for any unexpected outages. However, this paradigm is changing rapidly as the risky periods on the grid no longer occur at the time of peak demand, but at times

[i] According to the Energy Systems Integration Group, capacity accreditation establishes a way to measure the reliability contributions of individual resources to collectively meet the resource adequacy needs of the entire system. For more information, see: https://www.esig.energy/wp-content/uploads/2023/02/ESIG-Design-principles-capacity-accred-FS-importance-2023.pdf.

when demand is high and variable generation such as wind and solar are low. This is also known as high "net demand."

Stenclik highlights that while most planners "understand that the risk hours are shifting to the evening as the sun sets," not all yet recognize that the system risks will be "transitioning to winter—partially because of solar, but also due to cold snaps constraining gas supplies, increased electrification for electric winter heating, and the lower efficiency of electric vehicles in cold weather." Operators are also seeing more operational risk during spring and fall shoulder (non-peak) months, when grid capability is diminished because many generators and transmission facilities are taken offline for maintenance.[50]

> *"System risks will be transitioning to winter – partially because of solar, but also due to cold snaps constraining gas supplies, increased electrification for electric winter heating, and the lower efficiency of electric vehicles in cold weather" – Derek Stenclik, Founder, Telos Energy*

Furthermore, considering instantaneous periods of risk will no longer suffice. Increasingly, a new limiting factor for adequacy will be whether energy in one period is enough to charge batteries (or other storage technologies) to supply capacity later. While more sophisticated utilities and all ISOs already analyze risk across all hours of the year using chronological modeling, this approach is becoming more of a requirement than it has been in the past. Grid planners and operators will need to assess a diversity of portfolios against metrics like expected unserved energy and loss of load expectation that examine all hours of the year.

With weather systems typically confined to one region of the country, interregional transmission has been shown to provide significant resource adequacy benefits,[51] especially in high-renewable systems, because it allows regions to export and import during times of need that may occur with times of excess in other regions, as seen during Winter Storm Uri.[52] Demand response and energy efficiency, too, can be particularly important during short, rare events—they are much cheaper than new power plants, and can shift or reduce energy usage and reduce net load peak without having to build more power plants.[53]

These are just a few of the ways resource adequacy is evolving across the country, and several reports explore principles for this new paradigm in depth, such as a deep dive on capacity accreditation from Stenclik and the Energy Systems Integration Group.[54]

NEW POLICIES ARE NEEDED TO BRING A MANAGED TRANSITION TO FRUITION

No accreditation or probability calculation will be able to avoid reliability issues if we are not bringing new resources online apace of retirements and load growth. The risk of capacity shortfall is a trend that has increased over several years, largely because customer demand has been increasing and uneconomic coal plants are closing while new clean resources that could make up the retiring capacity have faced barriers to entry in many regions.[55] RTO/ISO markets and state regulatory environments will need to continue evolving to enable meaningful participation of clean energy technologies on the grid.

The interconnection queue presents one of the biggest sources of project delay and cost increases, but it is also an area where grid operators and utilities have the most control.[56] FERC Order 2023 has reckoned with many of the sources of interconnection delay,[57] but RTOs/ISOs should go even further.[58] One such reform that could represent a step-change in interconnection is allowing or simplifying an energy-only interconnection approach, which involves more limited studies and upgrades but requires resources to take additional curtailment risk.[59] The Electric Reliability Council of Texas (ERCOT) is also building numerous new transmission lines and upgrades relatively quickly. The combination of a fast interconnection process and relatively quick transmission expansion has allowed ERCOT to move record numbers of new clean projects through its interconnection queue over the last several years, with 52 GW of interconnection agreements executed between 2018 and 2020, or a 42 percent completion rate.[60] This is significantly faster than other regions—PJM only executed 6 percent of its interconnection requests during the same period, or 11 GW, despite operating a grid that is nearly twice the size. While an executed interconnection agreement doesn't translate directly to a completed project, the same pattern is seen in completed projects. ERCOT added more than 11 GW of new capacity to its grid between January 2024 and November 2024, while PJM added less than 3 GW in the same period.[61]

Beyond improving interconnection, the foundation of a managed clean energy transition is more holistic long-term resource planning that includes transmission to connect new generation to rising customer loads. To quickly increase transmission capacity, utilities and grid operators should use grid-enhancing technologies and advanced conductors to upgrade the capacity of existing transmission lines, in line with the recent resolution by the National Association of Regulatory Utility Commissioners.[62] Regional grid operators should also conduct proactive transmission planning and upgrade the system before power plant retirements or additions create costly new transmission constraints that keep uneconomic plants running.[63] While still a novel solution, utilities and grid operators should also tap into surplus interconnection[ii] as a tool to deploy electricity generation more quickly and enhance grid reliability.[64]

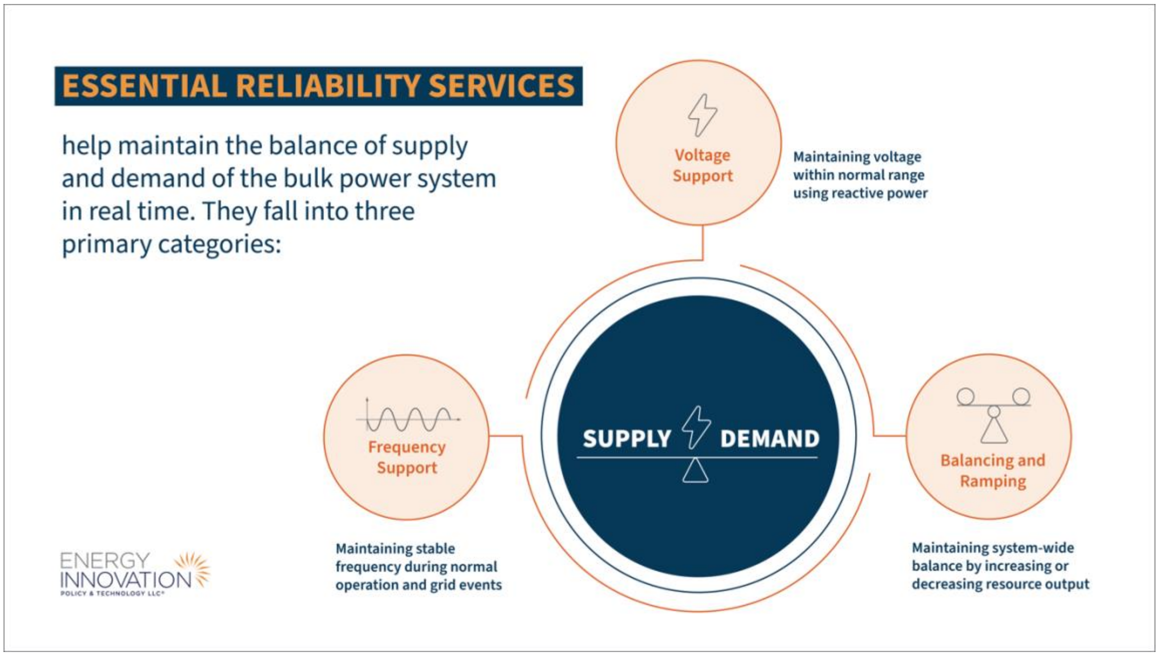
Importantly, the closure of old power plants is not the sole driver of resource adequacy concerns. Rather, piecemeal policies, unclear timelines, and a reluctance to embrace the clean energy transition already underway are halting progress. Misaligned objectives are creating unnecessary tumult for electric grid operators, regulators, and utilities alike. Now is the time to pivot from focusing on the technical feasibility of clean energy technologies to managing the clean energy transition in real time.

CHAPTER 3: REAL-TIME, RELIABLE OPERATION OF A DIVERSE PORTFOLIO

Grid reliability during real-time operation is determined in large part by the deployment of *essential reliability services (ERS)*, or *grid services,* which depend on the attributes and responsive characteristics of different energy resources. Essential reliability services fall broadly into three categories, as seen in Figure 3: frequency response, voltage support, and balancing and ramping. The electricity grid is subject to the laws of physics, which means electricity supply and demand must always be kept in balance to maintain relatively constant *frequency* and *voltage*. During normal operations, small changes occurring in each moment must be matched by corresponding changes in resource output to maintain balance. For example, Figure 4 shows the real-time frequency of the ERCOT grid during a two-hour span on December 5, 2024—the frequency fluctuates around 60 Hz but never moves far enough out of balance to cause greater instability.

[ii] According to GridLab, surplus interconnection allows new sources of electricity supply to connect to the grid at the site of an existing supply resource using the interconnection service already allotted to that resource, which offers a path to add new resources without the costly delays of the standard interconnection processes.

Figure 3. Essential reliability services fall into three categories

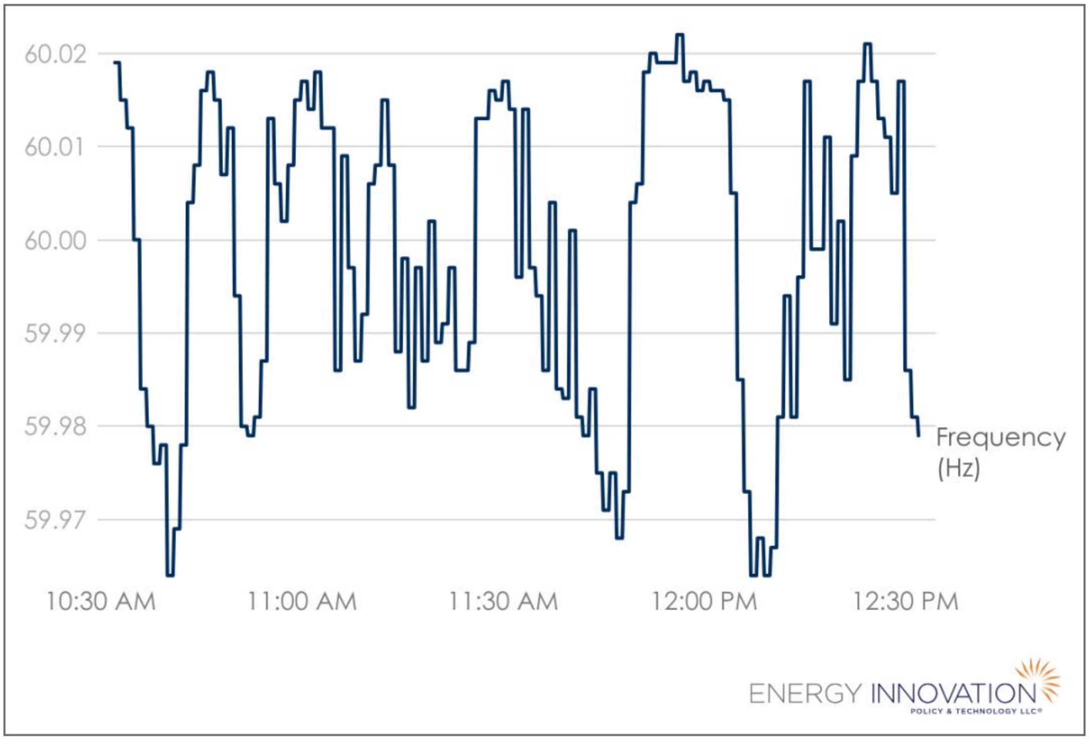


Essential reliability services are also known as ancillary services or grid services.

Think of a cup of water filled to the brim or a tightrope walker maintaining equilibrium. In either case, any disturbance beyond a nominal amount will result in a spill. Similarly, maintaining the balance between supply and demand in real time is paramount to grid reliability. In situations where the supply-demand imbalance becomes too large—for example, if a large power plant has an unplanned outage or high temperatures cause an unexpected spike in air conditioner use—the grid shifts to emergency grid operations. In these situations, extreme imbalances could lead to rolling outages or damage to equipment or appliances.

Avoiding these imbalances is the goal. Machines, technology, and software that operate to supply electricity all have different characteristics that enable them to respond to the laws of physics and provide different contributions to grid reliability. Importantly, not every resource must provide all types of reliability services, but the entire portfolio must be able to respond appropriately to bring the grid back to balance and resume "normal" operating conditions.

Figure 4. Real-time graph of ERCOT grid operating at a nominal frequency of 60 Hz on December 5, 2024

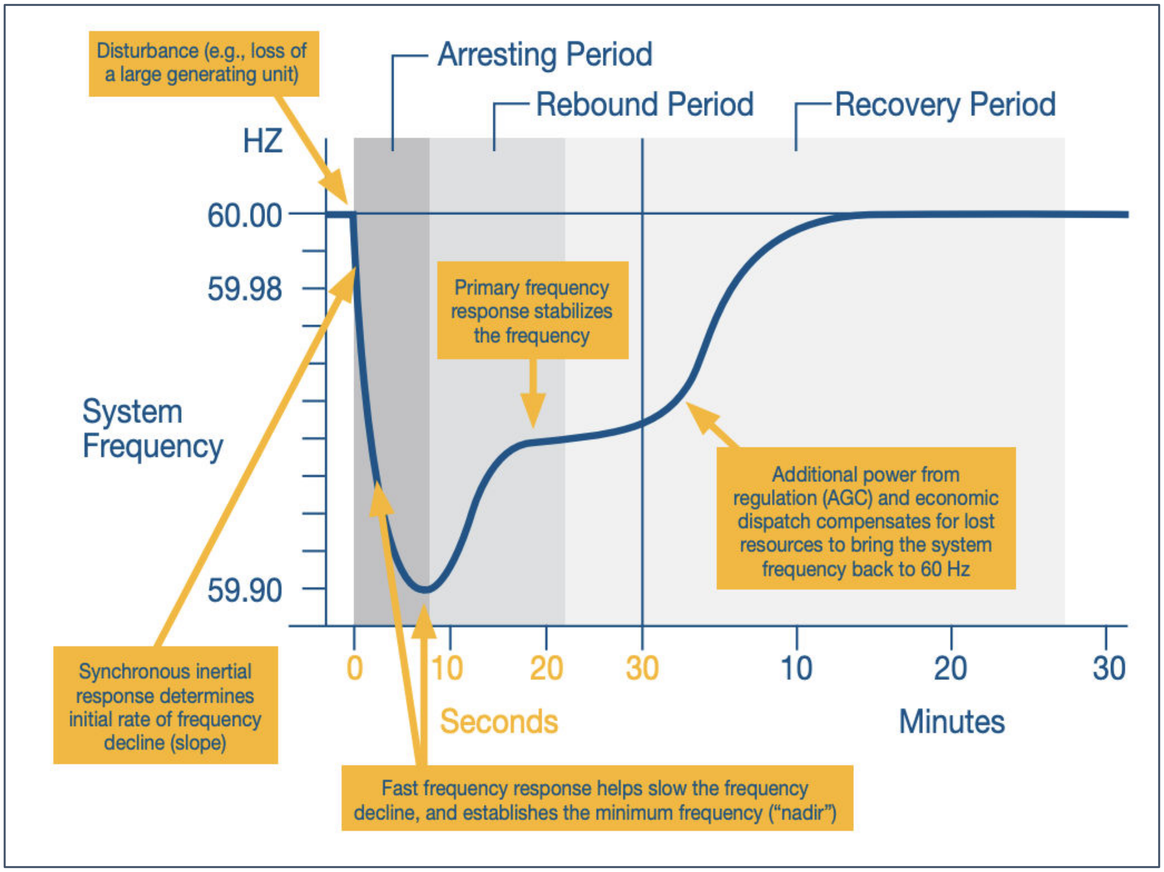


Data Source: ERCOT.

To maintain stability, each grid service available in the portfolio acts in a particular time frame. For example, fast frequency response occurs in the seconds immediately following a disturbance to slow decline,[65] and is followed by primary frequency response,[66] which stabilizes frequency. Economic dispatch, which as the name suggests is grounded in the relative cost of each available resource, typically operates at a five-minute time step.[67] Longer time steps are typically managed by automatic or manual dispatch through market mechanisms.[68] The entire portfolio must have some level of flexibility to provide essential reliability services in a changing environment.[69]

When more major disturbances occur, the portfolio must have sufficient disturbance ride-through capabilities to maintain frequency and voltage to keep resources online through moments of instability. In the case of a generator tripping offline, the grid's entire portfolio must be capable of providing reliability services to restore balance between generation and demand, as illustrated in Figure 5 below. If the system doesn't have enough reliability services and generation and storage capacity to fill in a sudden shortfall, the operator may have to shed some load (which results in a power outage for affected customers) to keep the system in balance and avoid a potential cascading outage.

Figure 5. An illustrative example of grid services working together to stabilize frequency



Source: Milligan Grid Solutions.

Similarly, the grid's voltage must be continuously maintained at nominal levels and be able to respond to disturbances. Maintaining stable voltage is critical to keeping the lights on and avoiding equipment damage, and it requires a different set of capabilities, such as reactive power control,[70] allowing for voltage control in the alternating current (AC) network.[71]

GRID SERVICES FROM CONVENTIONAL AND NEW TECHNOLOGIES

Grid operators traditionally obtained ERS from large thermal units and rotating machines (e.g., coal-fired, nuclear, and hydroelectric power plants) because the physical attributes of those machines provided the services needed. Their large, spinning masses provide inertia, which contributes to grid stability as supply and demand fluctuate. Large thermal plants are designed to be synchronized with the grid (i.e., synchronous generation), so if the frequency drops, the rotating inertia of the plant's turbine will continue and gradually slow the frequency drop, just like taking your foot off the accelerator in your car. This “coasting” bolsters the grid frequency so that other resources can respond, bringing the frequency back up to the right level, though over slightly longer time frames. While inertia slows frequency decline, it is not capable of restoring frequency back to its nominal level. Instead, services like fast frequency response, which can both slow the rate of frequency decline and help restore frequency, are needed to bring the grid back to normal operating conditions after a disturbance…

Traditional thermal plants are inherently slow and inflexible, and were designed for a grid that moves more slowly. Thirty years ago, demand did not modulate as rapidly as it does today, and customer equipment was less susceptible to outages in response to changing voltage and frequency. Today’s demand characteristics and technologies require faster reliability services and responses.

Over the past two decades, many old, inefficient, high-cost coal and natural gas plants have retired because they were too expensive to operate, could not be cost-effectively remediated to comply with updated regulations, and could not compete with newer gas-fired and renewable resources.[72] The retirement of those plants removed a significant amount of inertia from the grid, so upcoming retirements of remaining old coal plants are prompting new questions about how much rotating mass inertia is needed, as well as whether and how renewables and energy storage can provide frequency response services that mitigate a disturbance without using classic inertia.

Such a task is not straightforward. Grid reliability expert and former National Renewable Energy Laboratory Principal Researcher at the Electric Systems Integration Facility Michael Milligan explains that “new resources behave differently than incumbent resources.” For example, solar, wind, and batteries connect to the grid via inverters, which convert the direct current (DC) they generate to AC flow of the grid. Unlike their rotating machine predecessors (also called *synchronous* resources), these resources are *asynchronously* connected to the grid and either partially or completely interface through power electronics, which means they are not naturally in synch with the frequency of the grid. They can be programmed via their inverter and digital software to provide reliability services, but not always in the same way.

These *inverter-based resources (IBRs)* can ramp up and down much more quickly than a conventional power plant, making them more responsive to changing grid conditions. IBRs can provide nearly instantaneous fast frequency response, which results in a steeper slope of the initial decline, but frequency can be arrested much sooner than in the traditional case. Therefore, the decline in inertia caused by large thermal retirements and replacement by IBRs does not necessarily pose a problem for the grid. While frequency response offers one example, the entire portfolio of resources needs to provide a range of grid services, which is an evolving area of study of practical applications in real time. According to Milligan, “while there is an emerging recognition that inverter-based resources can provide certain grid services, we need greater awareness on how” and under what conditions.

For example, during summer heat waves in 2023, states and electric grids with more renewables and energy storage fared well.[73] These resources have helped balance the grid during times of spiking demand for cooling combined with the stresses of extreme temperatures on grid infrastructure.

Fortunately, we're learning that even in the absence of most or all inertial response, IBRs can respond nearly immediately after the triggering event. For example, with sufficient IBRs and accurate control settings, the frequency drop can be arrested more quickly, and the IBRs can even act quickly to help restore the nominal frequency. However, the technical characteristics and benefits of IBRs are not as well understood as thermal plant characteristics and operational practices, so more work is needed to build confidence in IBRs' ability to provide robust reliability services. One study compared the grid services from a wind plant, a gas plant, and a coal plant and found that wind could provide certain services faster.[74] More collaborative research and investigation into these capabilities is warranted now, before the retirements occur.

In addition, there must be a greater focus on strategies to integrate renewables and energy storage into markets and to compensate them in a way that reflects their ability to respond. For example, renewable energy developers may be disinclined to program their resources to ride through a voltage event if such a setting could compromise their asset or their operating revenues.[75] Going forward, utilities and grid operators should be working to quantify and understand how IBRs can respond during a grid emergency—in some cases, the IBRs may be able to provide a superior response, but they must be sufficiently compensated for doing so.

Batteries are one of the fastest-growing new resources,[76] and are untapped sources of reliability services. New advanced controls allow batteries to provide stability that traditionally has been delivered by conventional synchronous generators (known as grid forming). As these new battery resources come online, there is a ripe opportunity for evaluating their performance.[77] In fact, batteries are already showing their value—following a recent grid reliability event in Texas, which saw a large frequency decline that risked outages, energy storage helped stabilize the grid and return to normal operations.[78] Demand-side technologies also represent an untapped source of grid services (which we discuss more in Chapter 4).[79]

ADDRESSING UNCERTAINTIES ABOUT INVERTER-BASED RESOURCES

While IBRs are moving quickly to adapt their programming to enhance their grid performance, a few incidents with IBRs have caused concerns. For example, ERCOT has experienced utility-scale solar and wind generation tripping offline in response to a grid fault.[80,81] The largest of these events, the Odessa Disturbance 2 incident in June 2021, involved 14 solar facilities and resulted in the loss of more than 1.5 gigawatts of solar power.[82]

These incidents are uncommon, but they spotlight the need for appropriate responses to avoid their occurrence in the future. ERCOT has established an IBR working group to make recommended improvements and mitigate potential risks.[83] NERC has also formed an IBR performance task force working to develop innovative solutions.[84] The Energy Systems Integration Group is another notable collaborative network for research and emerging practices. The U.S. Department of Energy (DOE) and various national laboratories also play critical roles in supporting ongoing research and development efforts to support the grid's evolution.[85]

Ongoing efforts to achieve consensus around technical performance and any accompanying standards will aid grid operators eager for near-term solutions and new approaches.

OPERATING A RELIABLE GRID REQUIRES INSTITUTIONAL REFORMS

Multiple factors beyond technology affect reliability. In particular, energy market rules and economic incentives (often subject to government policies and regulatory interventions) dictate how energy resources and technologies can (and will) operate on the grid. Ideally, a combination of carrots and sticks can effectively influence grid reliability and performance. Grid rules and market signals should reflect the real-world operating characteristics of various technologies, which requires more awareness of the dynamic capabilities of IBRs. They should also allow and encourage resources to "show up" with the requisite grid services and in the quantities required by the laws of physics.

As more IBRs connect to the grid and ultimately replace retiring traditional resources over time, we need appropriate market mechanisms to ensure IBRs are prepared to provide needed grid services. Grid operators, working diligently to ensure the technologies available today are ready and available to provide the necessary grid services, have a role to play in facilitating needed changes: whether through programming a device or piece of equipment, or ensuring the settings allow for certain characteristics to be made available.

Several other processes must work to grow and maintain an effective clean energy grid. These include transmission planning and construction, generation interconnection queue management, well-defined and compensated grid reliability services products, and effective economic dispatch and market rules. Grid planning needs to incorporate a broad suite of potential future scenarios, including demand growth rates, climate-driven extreme weather, and continuing evolution of energy technologies and costs.

Policymakers and regulators should ask how grid planners and operators are evaluating the full potential of new resources to ensure the grid of the future can provide needed services based on new and emerging technologies. They should also evaluate market and reliability rules to ensure they are consistent with these technologies. Grid plans should evaluate the real and potential risks, including those caused by climate change-induced extreme weather, that will affect customer demands, generation assets, and transmission and distribution delivery systems. In the face of so many emerging and pervasive threats, grid planning is taking on a new level of importance.

"If you can't plan a reliable system, you can't possibly operate a reliable system." – Dr. Michael Milligan, Principal, Milligan Grid Solutions

As utilities and grid operators deal with mounting challenges resulting from more intense storms, solutions should aim to "make the grid larger than the storm," Milligan recommends. This could include more transmission between grid market regions, better coordination between grid systems on emergency response, and planning and working to ensure market rules sufficiently incentivize IBRs to provide grid services. Investments in grid hardening will also play a role in adaptation to climate change.

Beyond efforts to understand and embrace new technological capabilities, we need to ask better questions, such as, "How can fast frequency response replace inertia? How do we incentivize resources to provide needed services? Will market designs prevent or inhibit these incentives?" says Milligan. Collaborative research can help, but informed policies based on consensus research findings and the adoption of new approaches can facilitate an expedited evolution of the grid.

CHAPTER 4: DEMAND-SIDE SOLUTIONS

In fall 2023, Georgia Power filed an updated integrated resource plan with the Georgia Public Service Commission, warning that dramatic near-term load growth predictions from data centers required "immediate action" to meet capacity needs by the end of 2025. Its proposed solution set was a combination of three new natural gas power plants (with a combined capacity of up to 1,400 megawatts (MW)), several fossil fuel power purchase agreements, and a modest 150 MW residential demand response program.[86] In 2024, the projected demand growth increased, with the utility projecting over 36 GW of new large loads by 2035.[87]

Similar growth is occurring across the country, as electricity demand increases after more than two decades of nearly flat load growth. Numerous utilities and grid operators are revising their load forecasts, with Grid Strategies compiling over 100 GW in plans for new load by the end of the decade, compared to 2022 projections.[88] With these demand forecasts changing significantly year-over-year, the only certainty is that there is significant uncertainty. According to the Grid Strategies report, "These numbers may be an underestimate—or an overestimate. Greater uncertainty creates its own challenges, making it difficult to agree on planning scenarios, finance manufacturing, and complete the construction of transmission and generation."

Figure 6. Electricity grid planning areas with the sharpest increase in 2024 load forecast

Planning Areas with Greatest Increase in Summer 2029 Peak Demand

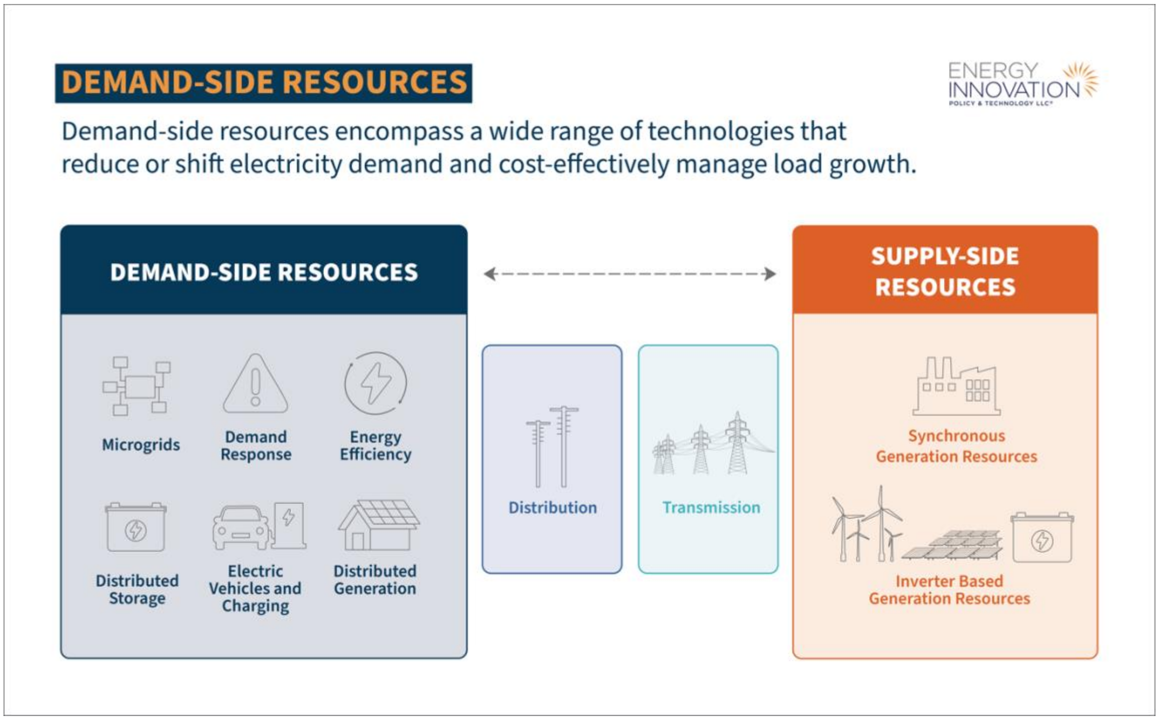
Planning Area	2029 Peak Demand 2022 Forecast (GW)	2023 Forecast (GW)	2024 Forecast (GW)	Forecast Updates (GW)	Forecast Increase (GW)	Forecast Increase (Percent)	Total Growth Through 2029 (GW)
ERCOT	84.4	89.6	88.1	+ 36.9	40.6	48.1%	42.8
PJM	153.3	156.9	165.7	+ 15.2	27.5	18.0%	29.6
Georgia Power	16.3	17.3	22.4	+ 7.3	13.5	83.1%	13.0
MISO	132.4	133.0	138.4		6.1	4.6%	9.1
Pacific Northwest	37.4	38.4	38.5	+ 2.0	3.1	8.2%	7.4
SPP	56.6	59.5	62.5		5.9	10.4%	6.3
Duke Energy (North & South Carolina)	33.9	36.2	36.6		2.7	7.8%	2.6
Arizona Public Service	8.7	9.8	9.9		1.2	13.6%	1.5
NYISO	31.5	32.3	32.3		0.9	2.8%	4.6
Tennessee Valley Authority	31.8	32.4	32.5		0.7	2.2%	1.4
All other planning areas	251.2	250.5	249.5		-1.7	-0.7%	10.0
Total	840.5	858.9	879.8	+ 61.4	100.7	12.0%	128.2

Source: Grid Strategies. December 2024.

However uncertain, rapid growth is causing panic over potential capacity shortfalls and insufficient transmission, prompting calls to delay planned coal plant retirements and build new natural gas plants.[89] But these fossil-intensive *supply-side solutions* are inherently slow and costly. They're also incompatible with utility and business climate commitments to hit net-zero emissions by mid-century. While strategic new generation and transmission solutions are needed to meet growing demand, these large investments will show up on electric customers' bills for decades to come and could increase emissions without helping affordability or sufficiently improving reliability.

But aggressive investments in *demand-side solutions* are a cost-effective, least-regrets way to manage growth in the near term, while unlocking their full potential over the long term. Demand-side solutions—namely, energy efficiency, demand response, customer-sited storage and distributed generation, and aggregated virtual power plants—can respond to rapidly changing grid conditions and support grid reliability amid the unpredictability of climate change. Although their decentralized and distributed nature makes them harder to plan for and manage, a growing ecosystem of providers and strategic regulatory efforts are working to overcome these barriers. Demand-side solutions can be challenging to implement because they require motivating, funding, and coordinating investments and action by thousands of customers. But these solutions can be designed to target and manage peak period loads and to geotarget and relieve areas of the grid that are overburdened, thereby reducing risk and uncertainty by slowing total demand growth and buying time for new transmission and generation builds. Energy efficiency and behind-the-meter storage and generation also enhance total system affordability and improve resilience for the customers and communities hosting these resources as extreme weather threats become more frequent and severe.

Figure 7. Demand-side resources



Utilities and grid operators should prioritize demand-side solutions alongside supply-side solutions and work with customers to deliver valuable grid services. Similarly, policymakers and regulators should adopt policies encouraging demand-side resources using a combination of technology-neutral carrots and sticks, increase visibility on the demand side, enable data sharing, support innovative grid planning methods, and overcome misaligned incentives.

A RAPIDLY SHIFTING LOAD LANDSCAPE

A May 2024 Brattle Group report documents the rapidly changing landscape for utilities and grid operators, largely driven by new electricity demand from data centers, onshoring manufacturing, agricultural and industrial electrification, cryptocurrency mining, and electrification.[90]

According to the report, in 2023 data centers alone represented 19 gigawatts (GW) of U.S. electricity peak demand, which is nearly double New York City's 2022 peak load of 10 GW. New research from the Electric Power Research Institute forecasts that data centers could consume up to 9 percent of U.S. electricity generation by 2030—double the amount consumed today.[91] Goldman Sachs estimates 47 GW of incremental power generation capacity will be required to support U.S. data center power demand through 2030, driving $50 billion in cumulative capital investment over the same time frame.[92]

Not all demand sources are created equally. For example, data centers or cryptocurrency mining are large and can come online relatively quickly, requiring huge amounts of energy nearly instantaneously, challenging traditional grid planning and operation paradigms. While utilities are eager to expand their infrastructure and rate base to serve these new loads, some policymakers and customer advocates are less enthusiastic. The amount of new load that data centers and crypto miners want often exceeds existing grid capacity and requires large investments to accommodate. In many places, these loads are creating scarcity and congestion that risk driving up electricity costs for all existing customers, absent creative solutions. Some regulators are exploring whether utilities have the same obligation to serve these new industrial customers.[iii] In some places, data centers are working directly with utilities to build or contract for new generation to serve their needs, which can help alleviate the strain on the grid and other customers, while also bringing new clean energy resources online. These arrangements typically require regulatory approval and dedicated tariffs distinct from traditional ratemaking paradigms.[93] But, if successful, such arrangements can ensure utilities and large load customers can meet demand cleanly and reliably.

Other demand sources like transportation and building electrification have longer lead times and steadier growth rates, making them easier to forecast and plan for. Some loads, like certain manufacturing facilities, are more elastic and capable of quickly scaling back or shuttering operations in response to changing electricity prices,

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[iii] For regulated energy utilities, the obligation to serve is a statutory requirement for utilities to offer service to any entity that requests it in their service territory.

whereas others may be more inflexible, like large industrial facilities that operate 24/7 to optimize their processes.

"Everyone is clutching their pearls over data centers and crypto, but every time we have a polar vortex or heat wave, similar load increases materialize to serve human needs like heating and cooling, but in much shorter time span. We cannot assume demand is immutable." – Alison Silverstein, Principal, Alison Silverstein Consulting

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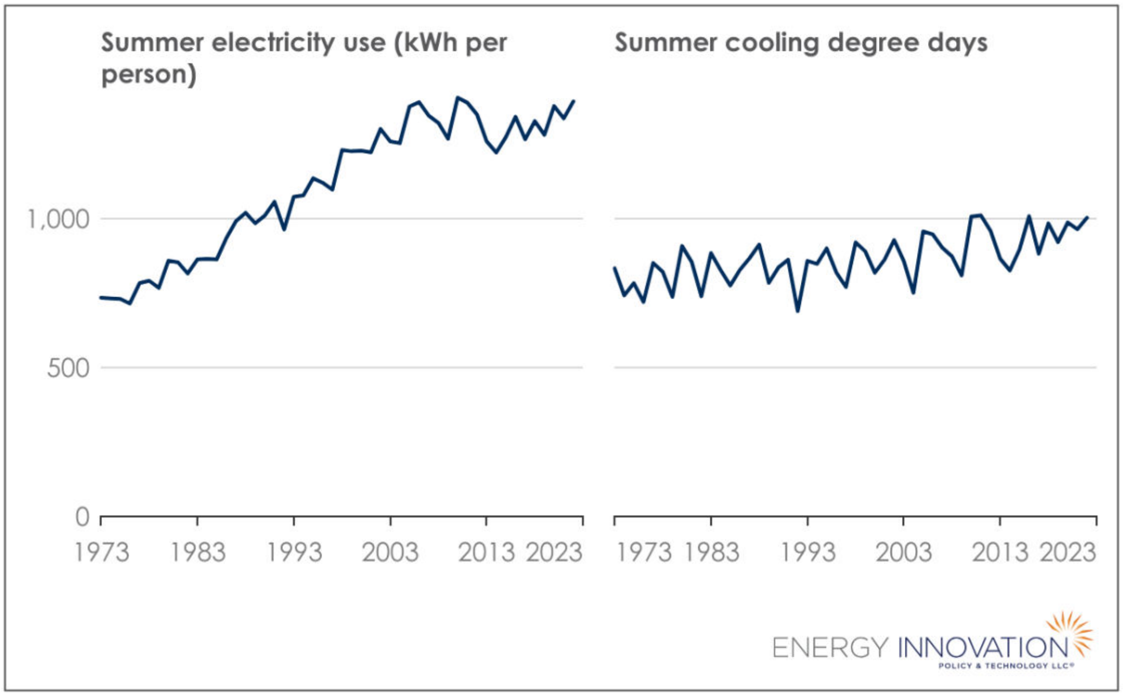
Electricity customers capable of reducing their impact during peak times could drastically reduce the need for new supply-side resources (thus bringing economic value to the grid and other customers). But capitalizing on this demand flexibility potential requires adequate incentives and strict rules. For example, customers with backup generation and batteries to protect their operations against grid failure could also be incentivized to provide grid flexibility services under certain conditions, but the benefits must be worth the costs to make it worth their while.

In addition to the loads themselves, climate-driven extreme weather is disrupting tried-and-true approaches to managing the grid and expectations about grid threats. "Everyone is clutching their pearls over data centers and crypto, but every time we have a polar vortex or a heat wave, similar load increases materialize to serve human needs like heating and cooling, but in a much shorter time span," says electric reliability expert Alison Silverstein. "We cannot assume demand is immutable. With climate change-driven weather shifts, demand has become less predictable, and at times terrifying."

Figure 8. Residential electricity use per capita and summer cooling degree days in the U.S., 1973 – 2023



Data Source: U.S. Environmental Protection Agency, Climate Change Indicators: Residential Energy Use, available at: https://www.epa.gov/climate-indicators/climate-change-indicators-residential-energy-use.

In nearly every state, summer and winter peak loads are higher, longer, and harder to forecast than they used to be. Given the time and money required to build new generation and transmission to meet new demand, Silverstein argues, "We can't build our way out of this fast enough. Now is the time to activate more energy efficiency and demand-side solutions, which are cheaper and faster to deploy, and can also buy us time to make prudent supply-side resource adjustments."

DEMAND-SIDE SOLUTIONS ARE READY TO PERFORM

Demand-side solutions encompass a wide range of technologies and applications that have the "potential to moderate the growth of both electricity consumption and peak load," according to the Brattle Group. For example, energy efficiency measures such as high-efficiency heat pumps can reduce summer cooling-driven peak loads and cold weather heating loads, as does attic insulation and building envelope improvements. Distributed generation like solar, wind, and energy storage systems can be paired with smart inverters or smart appliances capable of responding to changing grid conditions; demand-side management, demand response, and managed EV charging can coordinate with automation to respond to economic or grid conditions to reduce the overall impact of EVs on the grid.

Energy efficiency acts like baseload power—always operating to reduce load, especially when targeted to key operating hours like peak and net peak periods. Automated and controllable demand response performs more like fast gas plants that can be dispatched and ramped quickly to meet grid operational needs. These tools can be used to manage demand to meet available supply, rather than using supply resources to chase unmanaged demand.

Communication and software tools, like distributed energy management systems, can make dispersed resources visible to utilities and grid operators so they can plan for and manage them in ways similar to larger supply-side resources. Third-party aggregators and consumer-facing program administrators also play key roles as liaisons between grid operators, utilities, and consumers, helping streamline the process of recruiting customers, managing incentives, and pooling participating customers into aggregated resource blocks that can respond to grid needs when called upon.

Lawrence Berkeley National Laboratory notes that recent improvements in broadband and local area communication and control systems are enabling faster coordination of demand-response resources, such as commercial building HVAC or refrigerated warehouse end uses, so that loads can be managed and dispatched as needed to support grid reliability.[94]

Demand-response programs deployed at scale can be highly effective at managing new load growth and serving existing load while contributing to grid reliability. These programs induce customers to reduce, increase, or shift their electricity consumption in response to economic or reliability signals. Most demand-response programs encourage utility customers to shift electricity consumption from hours of high demand (relative to energy supply) to hours where energy supply is plentiful (relative to demand). Future programs may signal customers to increase electricity usage when the grid has excess electricity generation from renewable resources like the wind or sun.

According to a 2019 Brattle Group study, nearly 200 GW of cost-effective load flexibility potential will exist in the U.S. by 2030—more than triple the existing demand-response capability, and worth more than $15 billion annually in avoided system costs (e.g., avoided investment in new generation, reduced energy costs, deferred grid infrastructure upgrades, and the provision of additional ancillary services).[95] This potential will expand as more consumers adopt grid-responsive electric technologies and equipment.

Numerous utilities across the country and globe are relying on demand-response programs to tap into flexible loads on the grid, and these programs are increasingly valuable in the face of extreme weather conditions. For example, in Texas, following the devastating Winter Storm Uri 2021, municipally owned utility CPS Energy launched a new winter program that enables the utility to modify consumers' demand through remote thermostat control during periods of high energy use.[96] Similarly, during a 2023 summer heat wave in Arizona, the state's three largest utilities called on more than 100,000 customers, who receive incentives for participating in the program, to reduce their electricity use (by modifying their air conditioner temperatures using smart programmable thermostats) by a total of 276 megawatts (MW) during peak afternoon and evening hours.[97] That amount of power is equivalent to just over half the capacity of an average-sized combined cycle natural gas plant. In the United Kingdom, electric utility Octopus Energy's flexible demand trials paid around 100,000 households to shift their energy from peak times in lieu of paying a fossil fuel generator to switch on.[98]

In addition, demand response and energy service aggregators are working in this space to monetize flexible loads and sell grid services to utilities and RTOs. Large customers and retailers can use demand response to reduce their consumption during high-cost periods, which reduces their bills or provides substantial economic benefits. For example, Westchester County, New York, has received over $1.5 million from NuEnergen, LLC to date for their participation in three summer demand-response programs. Westchester remains on standby to reduce its energy usage during times when the grid is strained, and once alerted of an event, the county reduces energy usage at some of its facilities.[99]

Similarly successful programs target businesses and large energy users, which often are motivated to participate in programs that will reduce energy costs. For example, Utility Ameren Missouri partners with energy management services provider Enel X to offer incentive payments for customers participating in programs reduce their energy consumption temporarily in response to periods of peak demand on the grid.[100]

These are just a sample of the successful demand-side programs across the country. Yet today's demand-response programs stack up to a mere 60 GW of capacity—about 7 percent of national peak-coincident demand—and residential and commercial customer programs contribute only 30 percent of that. In some states, less than 1 percent of peak is met with demand-side solutions, with only a handful of states exceeding 10 percent.[101] Extreme heat and cold events can cause residential and commercial heating and cooling loads to make up nearly half of peak demand for some states (like Texas). As climate change drives up ambient and peak temperatures and causes more extreme heat and cold weather events, better management of demand with strategic reductions and load flexibility will be essential for grid reliability and affordability.

Energy efficiency is another effective tool, particularly when efficiency programs are targeted to reduce customer energy usage during peak hours. Efficiency measures such as replacing inefficient resistance heating and air conditioners with highly efficient heat pumps, adding attic insulation, sealing ducts, and sealing building envelopes can all help reduce customer electricity use on hot summer afternoons and frigid winter mornings, while improving comfort and energy savings. According to Silverstein, efficiency measures deliver benefits including better resource adequacy, lower wholesale prices, reduced customer energy bills, lower grid infrastructure requirements, improved customer comfort and health, and decreased emissions of carbon and other pollutants.

A 2023 study from the American Council for an Energy-Efficient Economy shows that using 10 aggressive peak-targeted energy efficiency and demand response tools in Texas could reduce both summer and winter peak demand levels by 15 GW or more, at costs far below that of building comparable amounts of new gas generators.[102] Similar results are achievable in other states.

SHIFTING FROM SOLELY SUPPLY-CENTRIC TO INCREASINGLY DEMAND-CENTEREDSOLUTIONS

Although demand-side solutions have a proven record of success, their potential is even higher. The electricity grid is still largely designed and operated to ramp supply-side resources to meet shifting demand, not the other way around. And demand-side solutions face challenges in their ability to scale, which prevents them from providing grid services.

In the face of rapid growth combined with extreme and unpredictable weather, now is the time to shift away from solely supply-centric approaches to ones that activate demand-side resources and flexible loads to their full potential. Looking forward, as the U.S. electric system uses increasing amounts of variable and weather-dependent resources (i.e., solar and wind) to serve demand, we must shift the system to manage demand resources to meet available supply, rather than managing supply resources to chase demand.

Many utilities and grid operators recognize the promise of demand-side solutions, but most lack the tools or financial incentives to lean into them as significant, reputable resources to meet new load growth and ensure grid reliability and affordability.

For example, investor-owned utilities earn returns on large capital expenditures (i.e., new generation or grid infrastructure) and forgo shareholder profits when they rely on decentralized resources that reduce or delay those investments. Bulk system planning and distribution planning are typically siloed processes, and few states or grid operators require coordination between the two. Wholesale market rules make it onerous for smaller aggregated demand-side resources to participate in serving grid needs. Similarly, RTOs lack visibility at a granular level on the distribution system, preventing them from forecasting and planning for demand-side resources at scale. Scaled aggregation of multiple demand-side resources into reliable grid resources that utilities and grid operators can see and consistently count on requires proactive regulation and oversight of the market.

At the consumer level, program success hinges on people and businesses being willing and able to participate in programs, which may require adoption of new technologies, meaningful compensation for their energy use changes, and a certain level of trust in their utilities (or retail electric providers) and aggregators. Not all customers contributing to the grid are compensated in proportion to the value they provide. This could be fixed through the adoption of forward-thinking policies, reliability services pricing, and greater participation opportunities and competition between energy service providers and aggregators.

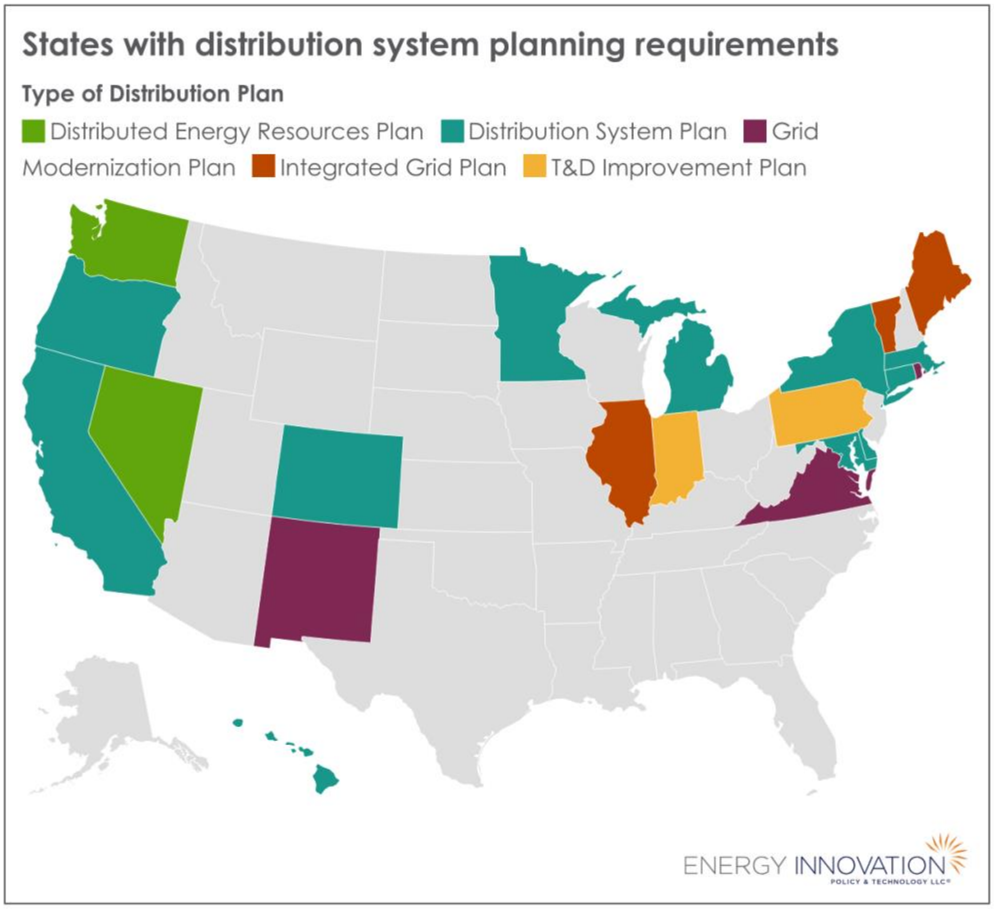
APPROACHES TO BOLSTER DEMAND-SIDE RESOURCES

First, utilities and grid operators need clearer visibility into demand-side resources. They want to know what's operating, how much, when, and with what impact. A combination of tools can improve transparency about the state of the grid and inform strategies for managing load, but all grid stakeholders need to be willing to adopt and use the tools to increase transparency on the grid. Examples of valuable tools include adopting distributed energy resource management systems or smart building management systems, utilizing more sophisticated models and control devices,[103] and allowing third-party aggregators to work directly with customers and utilities to administer effective demand-side programs. Bridging the gap between the supply side and the demand side to deliver guaranteed peak savings and other reliability services from load centers will require more coordination and communication among bulk grid operators and distribution grid utilities, distributed energy resources aggregators, and retailers.

Enabling data sharing across transmission and distribution systems is also important to unlock the full potential of demand-side resources while maintaining grid reliability. To facilitate productive information exchanges between different grid entities, NERC issued a reliability guideline to "provide clear recommendations and guidance for establishing effective modeling data requirements on collecting aggregate [distributed energy resources] data for the purposes of performing reliability studies."[104] Clear and consistent requirements developed by transmission planners and planning coordinators will facilitate the transfer of information between the distribution providers, resource planners, and any other external parties. According to Silverstein, "this includes real-time operational data, infrastructure, and load data to model how the grid will behave, and data used for planning and load forecasting." Data underpins visibility, but both sides of the grid need to agree on which data are most important and relevant (and how that data can be shared securely). Shared models that can communicate with one another and use data in the same way are also imperative. All data sharing must be subject to privacy and security protections, which also requires agreements among participating parties as to what gets shared, in what format, and who gets access.

In addition, ongoing efforts to improve load forecasts and grid planning approaches should continue with an eye to unlocking the full potential of demand-side resources over the long term. New tools are emerging that can inform more granular distribution planning efforts, such as integrated distribution system plans and publicly available hosting capacity maps. More than a dozen states require some type of distribution system planning, with several requiring detailed mapping of the distribution system at the circuit level.[105] Lessons from these states and guidance from national laboratories can inform others just starting down this path.[106] States that require utilities to develop integrated resource plans should also require detailed distribution system plans, and those two efforts should be closely coordinated.

Figure 9. States with distribution system planning requirements and type of plan



Source: Lawrence Berkeley National Laboratory. Interactive map available here: https://emp.lbl.gov/state-distribution-planning-requirements

In addition, regulators should consider adopting utility performance incentive mechanisms that reduce reasons for utilities to favor supply infrastructure over demand-side resources. These mechanisms can help shift the utility profit motive by aligning profits with performance on certain metrics, like successful demand-response or energy efficiency programs. In the era of load growth and climate change, performance incentive mechanisms should target measures that provide reliability and affordability benefits for all customers.

Finally, grid operators, utilities, and regulators should consider new approaches aimed at attracting more flexible and grid-supportive loads, while also placing customers at the center of program and rate design. This should apply across the electricity system, from the wholesale bulk grid down to the distribution system. Rate design and tariffs that encourage or require new load sources to respond to and react to grid conditions, economic signals, and reliability needs could obviate the need for more expensive alternatives down the line. For example, Google is piloting demand-response software that runs on its "carbon-intelligent computing platform" to reduce data center electricity consumption when there is high stress on the local power grid, with early successes in Europe, Taiwan, and the U.S.[107] Automakers and utilities are teaming up to expand managed EV charging programs to get ahead of load management before it becomes a problem at the local or system levels.[108]

But activating the full potential of demand response and demand-side management requires "respectful, negotiated limits with customers, who should be treated as partners and compensated fairly—their economic incentives should be commensurate with any perceived or actual sacrifice and with the value they deliver to the electric system," says Silverstein. Effective Programs should be designed to scale customer participation and optimize benefits for the grid and other ratepayers, par, including residential and lower-income customers. And energy efficiency programs should be designed and implemented to reduce loads during grid stress periods and geotargeted to relieve bulk grid congestion and rapid distribution system growth. In an era when multiple new loads are competing for the same space on the grid, utilities should consider rewarding those willing to go the extra mile for being a good grid citizen.

As electricity demand grows, so too should the role of demand-side solutions. A renewed focus on the load side of the equation will ensure a more cost-effective and efficient grid built to respond to rapidly changing conditions, while also benefiting and protecting customers and mitigating carbon emissions.

CHAPTER 5: CLEAN FIRM ENERGY

"Clean firm" energy is a term growing in currency: a catch-all phrase for a drop-in replacement for fossil fuel-based generation—the kind of resource that, if cost-effective and abundant, might be able to compete to provide on-demand energy in a deeply decarbonized grid. According to Wilson Ricks at Princeton's ZERO Lab, clean firm energy is defined as an energy source that generates electricity with zero- or extremely low-carbon emissions, and can do so "indefinitely, when needed, regardless of weather conditions."

The term includes resources like enhanced geothermal energy, advanced nuclear technologies, and forms of gas with carbon capture that can sequester nearly all the carbon produced. Sources of new demand, especially power-hungry data centers for artificial intelligence operating around the clock, are increasing calls to support and invest in these sources of carbon-free power that can serve data centers year-round, during times when wind and solar power are unavailable.

But clean firm energy sources will not be a silver bullet. While some clean firm technologies are promising, low-cost renewables have forever changed the calculation of what is the least-cost reliable generation portfolio. With today's technologies, clean firm resources may be best considered as part of a broader portfolio—one that relies on cheap wind and solar most of the time. The more expensive clean firm resources can then supplement wind and solar generation when their output is low, or demand is high—particularly during extreme weather or long droughts in wind and solar production. Clean firm can also play an important role in balancing inter-annual and inter-seasonal variation in wind and solar output. To fit this use case, ideally, the output from a clean firm resource is flexible, making it distinct from "always-on" power applications like legacy nuclear plants.

CLEAN FIRM ENERGY TENDS TO BE MORE EXPENSIVE

Eric Gimon, Senior Fellow at Energy Innovation, reiterates that because clean firm resources will ideally have flexible attributes, some clean firm resources are not necessarily best used in the 24/7 power applications that many imagine. Instead, he explains, clean firm resources that serve as an on-demand power source in a low-carbon grid are akin to safety features in a car: "Day to day, you need good brakes that won't fail, but you also want a seatbelt and an airbag even if they are not used all the time." Here, the clean firm energy technologies are the seatbelt and the airbag—they, or something else that can fit the same adaptable profile, are needed in extreme conditions but are not used 100 percent of the time.

This distinction is primarily economic—wind and solar are the cheapest sources of electricity, and they are available right now. To build the cleanest and most affordable grid as quickly as possible, we should primarily rely on these resources. Studies show that the U.S. could meet as much as 80-90 percent of its electricity demand with existing carbon-free sources and additions of low-cost wind, solar, and short-duration batteries.[109]

"The biggest myth about clean firm energy is that there is a choice to be made between the combination of wind, solar, and batteries, and clean firm energy. In reality, the most affordable system is going to be a combination of all of these because they each play a different role on the grid" – Wilson Ricks, Researcher, Princeton ZERO Lab

However, research shows that as the nation moves toward 100 percent clean electricity, using just new wind, solar, and batteries to maintain reliability is technically possible, but unlikely to be the lowest-cost approach.[110] This is due to the need to build additional resources as well as transmission capacity and storage so that electricity can be provided during infrequent extreme weather events or long periods of low production in wind and solar.

A portfolio of complementary resources can lower costs and provide better reliability. Clean firm energy sources perform well when other low-carbon options are limited, and the cheaper clean firm energy gets, the more it makes sense to include in the portfolio.

The biggest myth about clean firm energy, says Ricks, "is that there is a choice to be made between the combination of wind, solar, and batteries, and clean firm energy. In reality, the most affordable system is going to be a combination of all of these because they each play a different role on the grid."

CLEAN FIRM ENERGY NEEDS HELP TO DEPLOY

Nevertheless, the options to deploy clean firm energy at large scale right now are slim to none—a situation that needs to change if utilities are going to reach 100 percent clean electricity fast enough to meet U.S. and global climate goals.

In addition to the leading candidates for clean firm energy, renewable energy paired with multi-day energy storage technologies and applications of hydrogen could play a similar role on the grid by storing energy when it is cheap and releasing it for days or weeks at a time when it is scarce and expensive.

Hydropower can also be considered clean firm energy, and pumped hydropower is an important source of long-duration energy storage, but hydropower availability can vary significantly from year to year and is particularly exposed to the growing risk of droughts. Geographic limitations and impact of dams on river ecosystems also reduce the extent to which hydropower can be expanded in the U.S.[111]

Clean firm technologies are attracting increasing commercial interest. Enhanced geothermal, which uses novel drilling techniques to tap into underground heat, has seen a flurry of activity. Google and Fervo Energy collaborated on a 3.5 MW advanced geothermal power plant that is currently operational, and they plan to scale up significantly by 2028, when they expect to complete a 400 MW plant.[112] Long-duration energy storage is also progressing, with Form Energy scaling up manufacturing in West Virginia and undertaking pilot projects in New York, Minnesota, Colorado, and California that range from 5 to 10 MW.[113,114,115]

The DOE has been focusing on getting these technologies to a commercial "liftoff" point by early 2030s, which is defined as the point at which the market is self-generating demand for the technology.[116] For enhanced geothermal, for example, this means 2-5 GW deployed and a 60 percent reduction in levelized costs, down to $60/MWh on average and $45/MWh at the most competitive sites.[117] In the long term, the DOE expects that enhanced geothermal could reach average prices of $45/MWh by 2035, making it one of the most cost-effective clean firm generation resources, but only if it receives the necessary support.

The DOE Pathways to Commercial Liftoff effort recognizes the wide range of technologies that could work together to diversify the electricity mix and reduce the costs of reaching high levels of decarbonized electricity. These include virtual power plants, long-duration energy storage, and even upgrading the transmission system to increase electricity shared between and across regions.

Demand-side resources, as detailed in Chapter 4, can also provide significant benefits during times of peak electricity demand by ramping down or shifting demand to times when energy is more available. This is a particularly attractive solution because the cheapest power plant is the one that does not have to be built or use transmission and distribution capacity to bring power to customers.

These additional technologies may be just as important as clean firm energy, because the amount of clean firm energy needed to reach a reliable, 100 percent clean electricity grid varies depending on both the region and the other types of resources deployed. For example, in many cases, interregional transmission lines can significantly moderate variation in wind and solar output by creating a "grid bigger than the weather." In fact, interregional transmission lines have been shown to have significant reliability value, similar to a power plant.[118]

HOW TO SUPPORT DEPLOYMENT OF CLEAN FIRM ENERGY

Right now, the fastest and most cost-effective way to add much-needed grid capacity is using commercially available resources—wind, solar, and batteries. A recent analysis showed that if PJM had been able to bring online even 30 percent of the projects that entered the interconnection queue between 2015 and 2019, it could have added 7 GW of capacity by 2024 and brought auction prices 63 percent lower.[119]

In addition, new transmission is needed for all new resources, including clean firm technologies. Now is the time to double down on ongoing efforts to expand transmission capacity within and between regions, using both new construction and grid-enhancing technologies.

To continue advancements in clean firm technologies and ensure they are commercialized in future years when we need them most, policymakers, regulators, utilities, retailers, third-party developers, and large energy users should support and engage in ongoing research, development, and deployment. Regulators should initiate investigatory dockets on these potential resources, request information from vendors on technology status and cost, and independently evaluate the pathways toward commercialization. To help accelerate the technology learning curve and reduce costs faster, regulators should also allow partnerships between utilities, third-party generators, and large customers that want to take on the risk and cost of early deployment of clean firm technologies without exposing customers. Utilities should explore small-scale procurement activities to gain experience with initial commercial deployments.

CONCLUSION

The clean energy transition is well underway in the U.S. and around the world, and demand for carbon-free, reliable, and affordable electricity is rising. In the face of unprecedented changes and challenges, we need a commensurate shift in how we think about and approach grid reliability. Fortunately, the electricity grid has endured a myriad of evolutions since its inception. Now, it’s time to turn the technically feasible clean energy future into reality via a managed transition. Proper incentives are needed to bring forth new sources of energy and grid services; however, these incentives should be technology neutral and tied to a performance criterion. No single technology can meet electricity needs alone, and the grid has never relied on a single technology. Utilities should be investing in a diverse portfolio of clean demand- and supply-side resources capable of supporting an affordable, reliable, and carbon-free grid for all customers.

Today, we must plan, build, and operate a robust grid capable of riding through and bouncing back from extreme weather, without exacerbating harmful air pollution and climate emissions. Inherently slow and costly solutions are ill-equipped to address near-term capacity needs and transmission limitations. We should double down on flexible demand-side resources, adopt grid-enhancing technologies for transmission, clear queue backlogs and expedite new generation interconnections, and learn new ways of operating a diverse and resilient resource portfolio. Simultaneously, we need to lay the groundwork for long-term needs like new transmission and clean firm energy.

With a clearer understanding of the fundamentals of grid reliability, policymakers can shape and guide adoption of more sophisticated solutions that optimize the attributes and functionality of today’s technologies. Now is the time to jettison outdated modes of operation, planning, and thinking, and to instead embrace innovation and ambition in the pursuit of the grid of the future.

APPENDIX – RELIABILITY KEY TERMS

- **Active power** is the power transmitted to loads and converted to useful forms of energy, such as mechanical, heat, or light. If active power demand exceeds production, frequency will decline until active power balance is restored.

- **Reactive power** does not perform useful work but is used to establish and maintain electromagnetic fields that are needed to generate, transmit, and convert electric power in the alternating current network. A shortage of reactive power can cause voltage to decline.

- **Automatic generation control (AGC)** is a system for adjusting the power output of multiple generators at different power plants, in response to changes in the load. AGC and economic dispatch compensate for lost resources to bring the system frequency back to stable levels (60 Hz in the U.S.).

- **Capacity** is the amount of power a resource can provide to the grid at a given time.

- **Disturbance ride-through** refers to the ability of a piece of grid equipment to stay connected to the grid through a short-term disturbance, thus helping keep the grid stable through the disturbance. Inverter-based resources can provide disturbance ride-through services, but require specific design of their control system to do so.[iv]

- **Power** is the rate of transfer of energy.

- **Frequency** is the rate at which an alternating current changes direction, as measured in hertz (Hz). Across the power grid there is a consistent frequency, which in the U.S. is 60 Hz.

- **Voltage** is effectively the pressure that pushes current along a circuit. It is not consistent across the grid, though it is locally constant, with higher voltages used for longer transmission lines and lower voltages used at the distribution level. Transformers are used to increase and decrease voltages at grid interfaces.

- **Capacity accreditation** is the process for determining a resource's contribution or value to electricity capacity needs throughout the year.

- **Clean firm energy** is an energy source that generates electricity with zero- or extremely low-carbon emissions, and can do so when needed, regardless of weather conditions. Clean firm energy resources are distinct from "always-on"

[iv] Adam Maloyd, "The Complexity of Renewables, Part 4," PSC Consulting, March 30, 2023,https://www.pscconsulting.com/the-complexity-of-renewables-part-4/.

baseload power applications. They include enhanced geothermal energy, advanced nuclear technologies, and forms of gas with carbon capture that can sequester nearly all the carbon produced.

- **Demand-response programs** induce customers to reduce, increase, or shift their electricity consumption in response to economic or reliability signals. Most of these programs encourage utility customers to shift electricity consumption from hours of high demand (relative to energy supply) to hours when energy supply is plentiful (relative to demand).

- **Demand-side solutions** encompass a wide range of technologies and applications that have the potential to moderate the growth of both electricity consumption and peak load.

- **Distributed energy management systems** are communication and software tools that make dispersed resources visible to utilities and grid operators so they can plan for and manage them in ways similar to larger supply-side resources.

- **Disturbance** refers to a change in voltage, current, or frequency on the grid that brings it out of normal operating ranges. This could occur due to the loss of a large generating unit or another grid asset such as a transmission line or transformer.

- **Economic dispatch** is grounded in economics and typically operates at a five-minute time step; longer time steps are typically managed by automatic or manual dispatch through market mechanisms.

- **Energy efficiency measures** include replacing inefficient resistance heating and air conditioners with highly efficient heat pumps, adding attic insulation, and sealing ducts and building envelopes. These measures can help reduce energy use, provide energy savings, improve comfort, and increase property values.

- **Energy-only interconnection approaches** involve more limited studies and upgrades but require resources to take additional curtailment risk. This process has allowed Texas' ERCOT to connect record numbers of new clean projects in the last several years significantly faster than other regions. Also called connect-and-manage, or ERIS.

- **Essential reliability services** are the contributions that different resources provide to maintain stability, such as frequency response and voltage regulation. These services depend on the attributes and responsive characteristics of different energy resources.

- **Frequency regulation or response** is the ability of the grid to react to a change in the grid frequency to bring it back to the normal operating frequency.[v]
    - **Inertial response** refers to the injection of stored energy, such as kinetic or battery energy, into the electricity grid to slow down a decline in frequency. It determines the initial rate of frequency decline ("slope").[vi]
    - **Primary frequency response** works to stabilize frequency. It is an automatic and autonomous response to frequency variations through a generator's droop parameter and governor response, energy injection by grid-following inverters, or response by load. [vii]
    - **Fast frequency response** consists of the combined characteristics of inertial response and primary frequency response. It injects energy in the seconds immediately following a disturbance to slow frequency decline and establishes the minimum frequency (called the nadir).[viii]
    - **Secondary frequency response** works on a slightly longer time frame than primary frequency response, on the order of 5-15 minutes. It maintains grid frequency and allows for scheduled energy transfers between balancing authorities.[ix]
- **Grid forming** refers to the ability of an inverter to actively control frequency and voltage on the grid.
- **Grid following** refers to the ability of an inverter to synchronize with frequency and voltage on the grid.
- **Grid hardening** refers to myriad technology and operational solutions that help the grid withstand major events, such as extreme weather or natural disasters, without disruption.
- **Inertia** is the tendency of an object in motion to stay in motion (or an object at rest to stay at rest). In the context of the grid, it historically consists of the energy stored in generators as they rotate in sync with the frequency of the grid. It refers to the grid's ability to resist changes in frequency. Traditionally, inertia was provided by the large spinning mass of turbines at power plants such as coal, gas, nuclear, and hydro.

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[v] Paul De Martini, "Bulk Power, Distribution, and Grid Edge Services Definitions" (U.S. Department of Energy, November 2023), https://www.energy.gov/sites/default/files/2023-11/2023-11-01%20Grid%20Services%20Definitions%20nov%202023_optimized_0.pdf.
[vi] De Martini, "Bulk Power, Distribution, and Grid Edge Services Definitions."
[vii] De Martini, "Bulk Power, Distribution, and Grid Edge Services Definitions."
[viii] De Martini, "Bulk Power, Distribution, and Grid Edge Services Definitions."
[ix] De Martini, "Bulk Power, Distribution, and Grid Edge Services Definitions."

- **Synthetic inertia** is inertia provided without synchronous generators and refers to the transfer of active power into the grid from a grid-forming inverter. This type of inertia can provide the same, or even better, stabilization services as traditional inertia because it has an instantaneous effect.

- **Interconnection** refers to the process by which a new generator or load is connected to the grid.

- **Interconnection queue** is the line in which a new generator or load must wait to connect to the grid. While in the interconnection queue, the grid operator performs physical and economic studies to determine what infrastructure is needed to connect the resource or load to the grid while maintaining operational reliability.

- **Inverter-based resources** are generation resources that connect to the grid via inverters that convert the direct current they generate to alternating current flow of the grid. They can be programmed via their inverter and digital software to provide reliability services. Includes solar, wind, and batteries. Also referred to as asynchronous resources.

- **Inverter** refers to a device that converts direct current to alternating current. It is used to convert power output from solar cells, batteries, and wind turbines into power that can be injected into the grid.

- **Peak demand** is the highest amount of electricity demand that a grid operator needs to plan for during resource adequacy planning processes.

- **Performance incentive mechanisms** refer to regulatory incentives that hold utilities to a certain standard to guarantee a given return on equity, versus a guaranteed rate of return based on investment no matter performance.

- **Operational reliability** refers to balancing energy supply and demand in real time to maintain frequency and voltage within safe operating limits. It is the shorter-term dimension of reliability and requires regular monitoring and control of the entire grid.

- **Reliability** is a characteristic of the whole electricity system, to which individual resources contribute. Every source of electricity has different essential reliability services and operational characteristics that should complement each other in a balanced portfolio.

- **Resource adequacy** means having enough energy to meet demand—either in the form of supply-side generation or demand-side distributed resources. It is the longer-term dimension of reliability and requires planning in advance to ensure supply can meet forecasted demand.

- **Resilience** is the ability of the grid to ride through extreme events, recover quickly, and support other critical systems (e.g., transportation, health care, public safety etc.).

- **Synchronous resources** are generators with turbines rotating in sync with the grid frequency. They include large-scale thermal (coal and gas) and hydropower plants.

- **Voltage** of the grid must be maintained at nominal levels continuously and be able to respond to a disturbance. Maintaining stable voltage is critical to keeping the lights on and avoiding equipment damage.

- **Voltage support** consists of control over reactive power to maintain voltage levels within the correct range, typically 5-10 percent of nominal levels. It serves to maximize efficient transfer of real power to load and provide for operational flexibility. It is location specific and requires injection and absorption of reactive power from generators and transmission assets.[x]

[x] De Martini, "Bulk Power, Distribution, and Grid Edge Services Definitions."

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