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**THE RELIABILITY AND RESILIENCY OF ELECTRIC
SERVICE IN THE UNITED STATES IN LIGHT OF
RECENT RELIABILITY ASSESSMENTS AND ALERTS**

HEARING
BEFORE THE
COMMITTEE ON
ENERGY AND NATURAL RESOURCES
UNITED STATES SENATE
ONE HUNDRED EIGHTEENTH CONGRESS
FIRST SESSION

JUNE 1, 2023



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THE RELIABILITY AND RESILIENCY OF ELECTRIC SERVICE IN THE UNITED STATES IN LIGHT OF RECENT RELIABILITY ASSESSMENTS AND ALERTS

THURSDAY, JUNE 1, 2023

U.S. SENATE,
COMMITTEE ON ENERGY AND NATURAL RESOURCES,
Washington, DC.

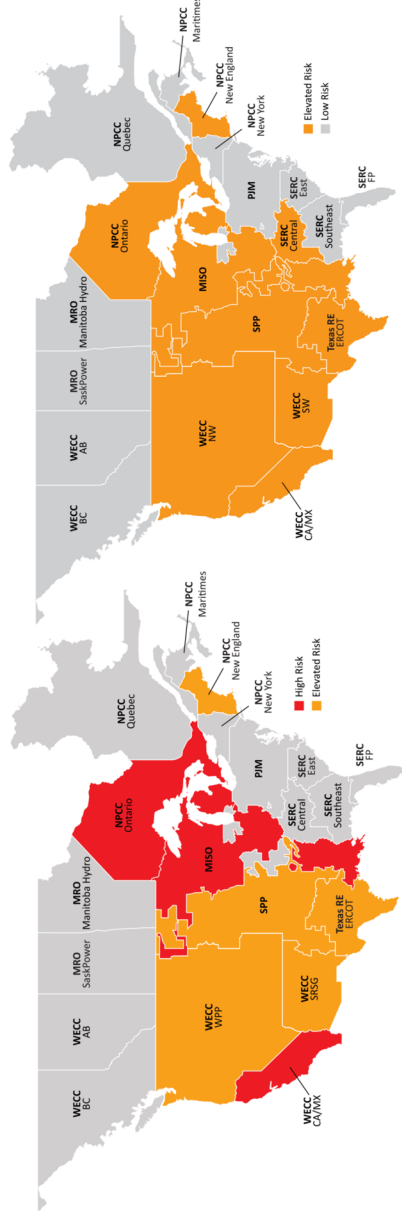
The Committee met, pursuant to notice, at 10:02 a.m. in Room SD-366, Dirksen Senate Office Building, Hon. Joe Manchin III, Chairman of the Committee, presiding.

OPENING STATEMENT OF HON. JOE MANCHIN III, U.S. SENATOR FROM WEST VIRGINIA

The CHAIRMAN. Today we are going to continue this Committee's ongoing oversight of the reliability challenges facing our electric grid. Reliable energy is foundational for any advanced economy and critical for families and businesses to thrive. And when electricity is unreliable, the potential consequences are nothing short of catastrophic, including the loss of human life. We know that our grid is most strained during the hottest and coldest periods of the year. That is why, before each summer and winter, the North American Electric Reliability Corporation (NERC) issues a reliability assessment, and the latest assessments have been frightening. The chart behind me shows NERC's short-term assessment for this summer and the long-term assessment for the next five years. The orange shows that we have a challenge and that the reliability is not certain. The red is serious, and for the next five years, just about the whole country is in a situation where we are not as reliable as we could and should be. Both assessments show two-thirds of the country facing reliability challenges as soon as this summer and lasting well into the future. I think all of us will agree that this is unacceptable, but it is not surprising.

[The chart referred to follows:]

Two-thirds of the United States Faces Reliability Challenges



NERC Long-Term Reliability Assessment
2023-2027

NERC Summer Reliability Assessment
2023

The CHAIRMAN. I have expressed strong concerns for years that this is what an unmanaged energy transition would look like. FERC and NERC have made recent efforts to develop new cold weather reliability standards to put us on firmer footing. These were much-needed steps, but more action is needed. And while increasingly extreme weather events are a part of the reliability challenge, we are also hearing growing concerns from grid operators across the country about losing our dispatchable generation resources before we are able to replace them. I want to take a moment now to remind everyone that all four FERC commissioners sat right where you are sitting and testified just last month that the grid will not be ready to operate without coal power in the near future, and if we want to maintain a reliable system, it must be there.

Yet through regulation after regulation, the Administration seems hell-bent on accelerating the premature retirements of our fossil plants. That is coupled with gaps in our power market designs that fail to require the right reliability attributes for renewables being added to the grid, and excessively long permitting processes are keeping us from bringing any new generation resources online in a timely fashion, whether it's fossil, renewables, nuclear—all of the above. We have a challenge. It seems the question is not if we will face another electric reliability crisis, but when. And the American people need us to do better than what we have.

Let me address federal regulations first. There is no doubt that our electric grid is undergoing a transition, both in generation sources and in the types of demand the grid is called on to serve. But the speed of this transition must be balanced against reliability and affordability of electricity. We know much larger portions of our grid would have experienced blackouts during Winter Storms Elliot and Uri if our coal fleet was retired prematurely. During these storms, coal power was one of the most reliable energy sources. But the EPA won't let electric reliability inconvenience their anti-fossil agenda.

Within six months of Winter Storm Elliot, EPA's response was to roll out four new regulations poised to shut down 50,000 megawatts or more of coal power over the next decade—whether the grid is ready for it or not. The only thing I would say to all of you, if you are concerned about that and what direction we are going and you don't want to make the mistake, talk to the Germans. Talk to Germany, and find out what they did, how it worked for them. EPA is not hiding their strategy. It is death by a thousand unreasonable cuts for fossil. For example, if you want to operate a fossil plant, the new proposed rules say that you are going to need CCUS, but the fact is, the Administration has not approved a single Class VI well permit that would allow captured CO₂ to be securely stored. Let me be clear—a requirement to use CCUS with a refusal to issue CCUS permits is a shutdown requirement. Congress has charged NERC with protecting the reliability of the electric system, but I am not sure the people are aware that agencies like EPA are not required to, and usually do not consult NERC about the reliability impacts of proposed new regulations on power plants. This makes absolutely no sense at all.

I know my colleague Senator Barrasso has legislation to change that, and I am also working on legislation to address this glaring omission. Having our environmental regulator work with our reliability regulator on power plant rules is just common sense if we don't want a catastrophe. This is something I would think every member of our Committee could support. We also know that the pressures on dispatchable power plants are not just a product of federal regulations, it is also driven by state policies and gaps in the way our electricity markets value reliability. At its core, this is a simple math problem. We are seeing more dispatchable resources shut down faster than new dispatchable resources are being added. We have seen over 90 gigawatts of coal power retire in the last decade, and we could see twice as much dispatchable capacity retire over the next decade on the path we are heading down. And by dispatchable, I mean controllable and flexible to meet supply and demand. Right now, that includes coal, gas, nuclear, and hydropower. And in the future, it will include renewables paired with storage, too. But the markets are not valuing dispatchable resources of any type properly to reflect the problem that we have. And the buck stops at our grid operators, like PJM, MISO, and certain utilities who are required by law to ensure NERC reliability standards are met.

Our markets have allowed renewables to receive the same payments as dispatchable resources without providing the same benefits to the grid. I want to acknowledge that PJM and other markets have recently taken initial steps to begin appropriately compensating the reliability benefits of different types of power plants, but much more is needed. This can't be more clearly demonstrated than in PJM's recent assessment that 40 gigawatts of existing generation are at risk of retirement by 2030, yet only about 30 gigawatts of equivalent capacity are projected to be added. And at the same time, demand on PJM is expected to grow by 15 gigawatts, resulting in declining reserve margins for the first time in recent history.

So I am interested to hear our witnesses' perspectives on market changes that would ensure these critical dispatchable resources are not retiring prematurely without adequate, reliable replacements. I also believe FERC needs clear authority to keep these reliability-critical generators from prematurely retiring and to issue regulatory exemptions as necessary so that ratepayers are not being penalized just to keep the lights on, because the impact of these collective EPA regulations is also a fairness issue. Take a coal plant as an example, which has already invested tens if not hundreds of millions of dollars on environmental upgrades, like scrubbers, bag houses, and low-NO_x boilers—and now could be required to spend tens or hundreds of millions more or else shut down. The investments already made have useful lives of decades, and ratepayers are going to be on the hook paying for them for decades whether the plant is shut down or not. It is ridiculous.

Is this Administration, which claims to be focused on equity, blind to the fact that the policies that they are pushing are going to harm low-income ratepayers in states like West Virginia, Wyoming, and all the other rural states by saddling them with unaffordable power while stripping them of reliable energy? For

generators that must remain online for reliability, we must not penalize their ratepayers by requiring hundreds of millions of dollars in additional environmental controls that will not ever be recouped in the remaining life of the plant.

I also want to speak briefly about electric transmission. The fact of the matter is that large, multi-state transmission lines are needed for reliability, but they are rarely getting built. And the wait to connect new generation to the transmission grid is growing at the same time that we need these resources more than ever. Wait times went from two years in the 2000s, to an average of five years by 2022. We have over two terawatts—that's two million megawatts—waiting in the queue. These delays are having real impacts on getting dispatchable generation onto the grid. In Doddridge County, West Virginia, a little county in my state, a new 1,800-megawatt natural gas plant with carbon capture is stuck waiting 68 months to get connected to the PJM transmission system. I am very glad to see important NEPA reforms included in the debt ceiling deal that myself and many of our members in this Committee have advocated for, which will help projects like this complete federal NEPA reviews in one to two years. But it takes five years to hook into the grid. That could become the bottleneck instead of NEPA.

So I think more needs to be done to improve federal permitting of all types of energy infrastructure, including transmission. I welcome our witnesses' perspectives on how permitting reform for all types of energy can benefit electric reliability, whether it is transmission lines to move electrons between states and regions, pipelines to better supply our gas generators, or anything else it takes to get reliable energy in our country. Your input will help inform our Committee's future work on permitting. Our Committee has responsibility for ensuring that our federal power laws and energy agencies are promoting reliable electricity for the nation. I am confident we can develop bipartisan proposals to better equip NERC and FERC and the electric industry with tools to address the reliability threats the grid is facing. All four of our witnesses have provided suggestions for Congress to act in their written testimony, including increasing the involvement of our reliability experts in developing environmental regulations, better management of the pace of retirements, permitting reforms, and several other ideas worth considering.

So I look forward to hearing recommendations from each of you about the most impactful steps that we could take as a Committee.

With that, I turn to Senator Barrasso for his opening remarks.

**OPENING STATEMENT OF HON. JOHN BARRASSO,
U.S. SENATOR FROM WYOMING**

Senator BARRASSO. Well, thanks so much, Mr. Chairman.

And first, I do look forward to continuing to work with you on permitting reform. As you said, there is more we can do. There is more we should do. There is more we need to do. And that is why I have joined with every Republican on this Committee in introducing the SPUR Act. It stands for Spur Permitting of Underdeveloped Resources Act. And America needs to generate more—not less—energy. We need more home-grown energy—natural gas,

coal, uranium. You name it, we need it all. We need to have a reliable electric grid. That means generating more, not less, reliable and available and affordable power. A transmission line without reliable and available electricity is like a stream bed without water flowing through it. So as we continue to work on permitting reform, Mr. Chairman, we need to focus on producing more reliable American energy and not just on how to transport it.

So with that, Mr. Chairman, I am so grateful that you called today's hearing. Reliable, resilient, affordable electric service is indispensable to our nation. When the electric grid fails, it puts our other essential services at risk or makes them unavailable. The consequences are catastrophic. There is no disputing the fact that electricity needs to be produced at the instant people call for it. Men and women who enable our electric grids to work must hold production and demand in balance all the time. They must do this year in, year out, no matter what time of day, no matter what the weather happens to be. No excuse. No finger pointing is acceptable when an electric system fails.

We know the sad reality. Electric service in this country is at an increasing risk—an unacceptable risk of failure. One can't predict blackouts, yet given current trends, one can reasonably project that we will have more of what regulators are calling unplanned outages. The writing is on the wall. Summer 2020—California's energy policies left the state's electric grid operators with no other choice but to impose rolling blackouts on its residents. February 2021—cold weather and insufficient baseload power resulted in a major blackout in Texas. December 2022—cold weather and a failure to secure sufficient natural gas nearly led to a blackout in the entire mid-Atlantic. After the 2021 blackout, two of the four witnesses before us today sat here at the same witness table and warned us of similar risks to the grid. They will warn us of that again today.

Just last month, members of the Federal Energy Regulatory Commission warned us of the same threats. Commissioner Danly said there is “an impending, but avoidable reliability crisis.” Commissioner Christie said, “there is a looming reliability crisis.” Neither Commissioner issued these warnings lightly. Commissioner Danly said, “I fervently hope to be proven wrong.” Commissioner Christie said, “I do not use the term crisis for melodrama, but because it is an accurate description of what we are facing.” Commissioner Christie put it succinctly when he said, “the problem generally is not the addition of intermittent resources—primarily wind and solar—but the far-too-rapid subtraction of dispatchable resources, especially coal and gas.” I think we are going to hear similar testimony from our witnesses today.

Electric grid operators must have access to a diverse set of resources. That includes coal, natural gas, nuclear, and hydropower, along with wind and solar. Electric transmission can help with a big challenge, weather related or otherwise, whatever comes along. Transmission helps one region lean on another. Still, we must have electrons to put on the transmission lines. We must address the problem of premature retirements of plants that generate power at all times. Wind and solar energy now supply about 15 percent of the nation's power. They do not replace always-on power. When the wind doesn't blow and the sun doesn't shine, we get no power. We

must acknowledge the indispensable value of power plants that generate electricity whenever they are called upon.

Last fall, President Biden said, “we are going to be shutting coal plants down all across America.” Just last month, the EPA proposed new regulations to shut down both coal and natural gas plants. President Biden is doubling down on reckless policies. They are a danger to our electric grid. We need to restore balance. President Biden’s Administration rarely lets a day go by without talking about what they mistakenly and inaccurately call the “Climate Crisis.” It is time they acknowledge their policies are creating a reliability crisis.

Thank you, Mr. Chairman.

The CHAIRMAN. Thank you, Senator Barrasso.

Before we go to the witnesses, I am going to turn to Senator Wyden because he has another pressing committee he has to go to. Senator Wyden.

Senator WYDEN. Thank you very much, Mr. Chairman.

And Mr. Chairman, I want to commend you for holding a very important hearing and make just a couple of points real quickly, and then I have a question that I am going to pose for the record to Mr. Tudor, who has been doing great work for the rural electrics.

In early summer of 2021, after designing it and writing it, particularly with the input of the Chairman, the Senate Finance Committee moved close to \$300 billion worth of clean energy tax credits, the biggest investment in energy security and climate in our country’s history. At the time—and we have a number of colleagues from the Committee, the Senator from Nevada, Senator Cortez Masto—we said we had two additional priorities, Mr. Chairman. And we started working on that. One of them you just mentioned in your testimony, and that is expanding transmission. We know that that is vitally important. And second, we have to harden the power grid. And Mr. Tudor, your folks were very helpful to us in the Disaster Safe Power Grid Act, which we got into the Bipartisan Infrastructure bill.

And my question, just so you will have it for the record is, I would like you, in the course of the morning, to outline the additional steps that your members in rural communities need to further harden the power grid. We know we are going to have another tough fire season. I am looking down the row here and my colleagues are going to be asking you about that too. This is not something that is an abstract kind of question. This is existential for western communities.

So thank you for your cooperation.

Mr. Chairman, you have been helping us from the get-go, and I remember those first days when you invited me to West Virginia and we will continue that cooperation.

I yield back.

The CHAIRMAN. Thank you, Senator Wyden.

And again, I want to say thank you to all of our witnesses today for being here. We appreciate it very much.

I want to introduce all of you.

We have Mr. Jim Robb, President and CEO of the North American Electric Reliability Corporation.

Mr. Manu Asthana—is that close?

Mr. ASTHANA. You got it.

The CHAIRMAN. Hot dog.

President and CEO of PJM.

We have Dr. Melissa Lott, Senior Research Scholar and Director of Research at the Columbia Center on Global Energy Policy.

And we have Mr. David Tudor, CEO and General Manager of Associated Electric Cooperative.

Mr. Robb, we are going to start with you.

STATEMENT OF JAMES B. ROBB, PRESIDENT AND CHIEF EXECUTIVE OFFICER, NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Mr. ROBB. Great. Well, good morning, Chairman Manchin and members of the Committee. It is a pleasure to be here. I appreciate the opportunity to discuss our views on the reliability and resilience of the electric grid, Ranking Member Barrasso, as well.

First of all, we believe that the electric power system is absolutely at an inflection point right now. The electric transmission grid is highly reliable and resilient, yet the risk profile to customers is steadily increasing. Our assessments demonstrate that the electric grid is operating ever closer to the edge, where more frequent and more serious disruptions are increasingly likely. We also believe that the energy transformation can be navigated in a reliable way. That is, of course, with the proviso that the pace of grid transformation is recalibrated with the reliability needs of the system.

Let me begin by reviewing four major factors contributing to this deteriorating risk profile. First, the foundation upon which the grid operates is out of balance. The system must constantly balance affordability, reliability, and environmental sustainability, and we are not making the required investments for reliability as the system transforms. NERC reliability assessments demonstrate this lack of balance. Our summer and long-term assessments, as you showed earlier today, show that the risk of energy shortfalls is increasing and spreading to more areas of the country. This is particularly true during periods of extreme weather, as we have experienced over the past five years, with broad area heat events impacting the West and widespread severe cold events impacting the eastern and southeastern portion of the U.S. This trend is being driven by disorderly retirements of conventional generating capacity—often coal, nuclear, and older natural gas; performance issues with replacement resources; energy uncertainty during increasingly frequent, wide-area, long-duration extreme weather events; and increased demand due to electrification policies coupled with the slow development of energy infrastructure.

The second, while the risk is increasing, the underlying performance of the electric grid that NERC oversees continues to improve, suggesting the success of the ERO model. In the bulk electric system that is under our direct jurisdiction, we see sustained improvements in human and equipment performance, leading to substantially reduced unplanned transmission outages. We have not had a major cascading failure of the system in over 13 years.

Third, a number of interrelated factors behind high-profile outages such as Winter Storms Uri and Elliot, the Summer 2020 out-

age in California, and a series of near-misses are driving risk. These factors include the performance of inverter-based resources, performance issues with generation under extreme weather conditions, fuel supply disruption, especially natural gas during winter conditions, and a general decline in the reliable generating capacity, which is removing the highly valuable slack in the system.

And fourth, I have to acknowledge that new technologies do offset some of these risks. Some of these emerging technologies that are being deployed have the potential, in the long run, to make a substantial difference, especially batteries.

So let me turn to solution space, beginning with NERC's actions. We are highly focused on the performance of inverter-based technologies to ensure that they can contribute to reliability and not compromise it during periods of stress, as we have experienced in multiple events. We are working to establish planning requirements that focus on energy sufficiency to meet 24/7 customer demands. Our efforts are focused both on near-term operations as well as long-term planning horizons. We are working to incorporate more extreme weather conditions and scenarios into our planning and operating requirements. To that end, we have also established FERC-approved weatherization requirements for generating plants. We are also focused on understanding and establishing performance requirements for the increasing number of generating facilities, often inverter-based, that are connecting at voltages below the level of the bulk electric system. It is important to note here that our goal is not to expand our jurisdiction, but simply to ensure that these resources support reliability.

And I will conclude here with a call for action in five areas outside of our direct jurisdiction. First, we absolutely need to rethink the policy and oversight of the intersection of the natural gas industry with the electric sector. Natural gas is the largest power generation fuel in the United States, and power generation is now the largest end-use consumer of natural gas. It is time that we acknowledge that and address the reliability and resilience of this key interface. Second, we need to ensure that the appropriate investments in reliability and fuel security are rewarded, particularly in the areas of the country that rely on power markets and market signals to drive investments in operating decisions. Next, reliability needs to be prioritized and policy decisions made by other executive branch departments that affect the pace of retirements. And because the low-carbon future requires significant investment in electric transmission and other energy infrastructure, we must break the back of the infrastructure siting challenge. And then, finally, we need to keep our foot on the gas, accelerating the deployment and development of new technologies, such as grid-forming inverters, energy storage, new nuclear technologies, and hydrogen.

As we continue to electrify the economy, reliability is going to only become increasingly important. And as I like to tell my team, nearly 400 million citizens across North America depend on a reliable supply of electricity to support their way of life. Thank you.

[The prepared statement of Mr. Robb follows:]

**“The Reliability and Resiliency of Electric Service in the United States
in Light of Recent Reliability Assessments and Alerts”
June 1, 2023**

**Before the Committee on Energy and Natural Resources
United States Senate
Washington, DC**

**Testimony of James B. Robb
President and Chief Executive Officer
North American Electric Reliability Corporation**

Introduction

The bulk power system (BPS) is at an inflection point. The electric transmission grid is highly reliable and resilient, and has grown more so under the current reliability regime. Yet the risk profile to customers is steadily deteriorating. Factors contributing to this deterioration include:

- Rapid, often disorderly transformation of the generation resource base,
- Performance issues associated with replacement resources as conventional units retire,
- Wide-area, long duration extreme weather events, which are becoming more frequent,
- And increased demand due to electrification, coupled with slow development of new energy infrastructure needed to support grid resilience and the clean energy future.

Independent technical assessments by the North American Electric Reliability Corporation (NERC) find that the energy transformation can be navigated in a reliable way, provided reliability is recognized as a central priority. NERC is concerned that the pace of change is overtaking the reliability needs of the system. Unless reliability and resilience are appropriately prioritized, current trends indicate the potential for more frequent and more serious long duration reliability disruptions, including the possibility of national consequence events.

Outside of cyber/physical security, which presents complex issues worthy of separate discussion, three reliability priorities must be addressed:

- First, we must manage the pace of the transformation in an orderly way, which is currently not happening. Conventional generation is retiring at an unprecedented rate.
- Second, we must identify new resources to replace retiring generation that provides both sufficient energy *and* essential reliability services (such as flexibility, voltage support, frequency response, and dispatchability) needed for stable grid operations.
- Finally, we must shift focus from planning for solely “capacity on peak” to “energy 24x7” due to the changing fuel mix. Further, we need to better understand the impact on the bulk power system from the dynamic performance associated with inverter based resources (IBRs) and distributed energy resources (DERs). These understandings can then

be balanced against the potential for demand side management (both energy efficiency and demand response) to support reliability and resilience.

Within the limits of Section 215 of the Federal Power Act, NERC acts as a reliability regulator for the BPS. NERC has authority over transmission and generation facilities needed to maintain transmission system reliability. However, NERC may not order the enlargement of these facilities, nor may NERC require construction of new transmission or generation capacity. Furthermore, local distribution of electricity and fuel supply are excluded from NERC jurisdiction and fall under State oversight. While the current reliability regime significantly strengthens reliability of North America's transmission system, transformation of the generation resource mix and the expansion of DERs have injected new jurisdictional complexities. Adding to these challenges is the need for industry, regulators, and policymakers to constantly balance reliability with customer affordability and environment impacts, priorities that are outside of NERC's jurisdiction. When viewed through the lens of balancing reliability, economics, and the environment, the challenges for the electricity sector become highly complex.

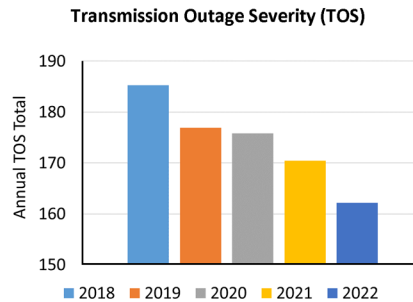
With a highly reliable, resilient, and secure BPS at the core of NERC's mission, our focus is on proactively addressing the reliability risks of the transforming grid. This testimony examines the growing potential for regional energy shortfalls across North America, NERC's actions to mitigate this risk, and next steps for industry, regulators, Congress, and other policymakers.

While the Transmission System is Highly Reliable, the Aggregate Electric System is Threatened by a Deteriorating Risk Profile

When the Federal Energy Regulatory Commission (FERC) designated NERC as the Electric Reliability Organization (ERO) in 2006, establishment of a mandatory regime focused on transmission system reliability was the central focus. Through a suite of mandatory enforceable standards, the goal was to align the electricity industry along a common set of essential practices to mitigate reliability risks. Reliability Standards are aimed at avoiding instability, uncontrolled separation, and cascading within an interconnection. While reliability risk mitigation is a complex endeavor, Federal Power Act Section 215 has the distinct advantage of direct jurisdiction tailored to addressing the most pressing risks existing at the time.

The ERO model has been highly successful in reducing risk. By objective measures, today's BPS transmission system is demonstrably more reliable and resilient. Many conventional risks that challenge the grid have now been reduced by significant margins and continue to trend in a positive direction overall. NERC's *2023 State of Reliability Assessment*—to be published later this month—documents a five-year trend of significantly improved transmission system reliability. This includes a system of declining equipment failures, improved human performance, better situational awareness, and effective vegetation management programs. There have been no cyber events impacting bulk electric system facilities, and there have been no outages associated with substations deemed critical to BPS performance and protected under NERC Reliability

Standards. Since 2016, the duration and severity of transmission outages in North America have declined by statistically significant margins.¹ The chart below depicts the decline in transmission outage severity, documented in the upcoming *2023 State of Reliability*. In short, the ERO model is paying significant dividends for the nearly 400 million North Americans who depend upon a reliable bulk power system.



Source: 2023 State of Reliability (to be published June 2023)

However, significant risks have emerged relative to the electricity supply for North America in ways that were not contemplated when the ERO model was established. Mitigation of these new and emerging reliability risks involves a multidimensional set of issues, including a rapidly changing generation resource mix, a changing climate, changing electricity demand profiles, and new technologies, some of which are not quite ready for full deployment. Successful navigation of these issues require multidimensional solutions, often requiring effective coordination of multiple jurisdictions, or examination of new authority where no jurisdiction effectively exists.

If “conventional risk” is defined by risks around which federal jurisdiction provides adequate mitigation, “new risk” is defined by risks to the BPS that cross jurisdictions, are the exclusive province of the states (such as resource and transmission adequacy, and distributed energy resources), or where jurisdiction is unclear or insufficient (such as the interface between the natural gas sector and the electric sector). Solutions to these risks are considerably more complex because, unlike conventional risks, new risks require coordinated engagement among differing jurisdictions or even the establishment of new jurisdictional authorities.

There are three key reliability priorities, outside of cyber/physical security, that will help us address these challenges and be successful. First, we must manage the pace of the transformation in an orderly way, which is currently not happening. Second, we must identify and integrate new resources to replace retiring generation that provides both sufficient energy and essential reliability services needed for stable grid operations. Finally, due to the changing

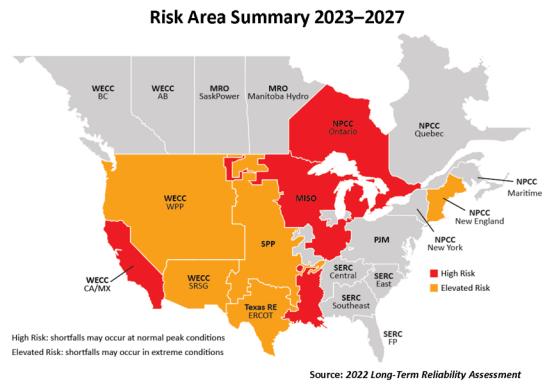
¹ NERC, *2022 State of Reliability: An Assessment of 2021 Bulk Power System Performance (July 2022)*, https://www.nerc.com/pa/RAPA/PA/Performance%20Analysis%20DL/NERC_SOR_2022.pdf.

fuel mix, the dynamics associated with DERs, and the potential for demand side management to support reliability, we must shift the planning focus. Whereas resource planning traditionally focused on having enough generation capacity during peak demand conditions (“capacity on peak”), the focus must be broadened to include the need for sufficient energy at all times (“energy 24x7”).

NERC Assessments Show Growing Risk of Energy Shortages

NERC's 2021 *ERO Reliability Risk Priorities Report*² finds that the rapid interconnection of BPS-connected IBRs and how they interact with the high voltage power grid and other resources is the most significant driver of grid transformation and poses a high risk to BPS reliability. The rapidly transforming generation resource mix elevates energy availability as a growing concern for BPS reliability. The dynamic performance of IBRs has not been satisfactory, further elevating the risks for shortfalls when events on the system are experienced. Whether looking out ten years or two months, the risk of energy shortfalls is real and is growing more acute.

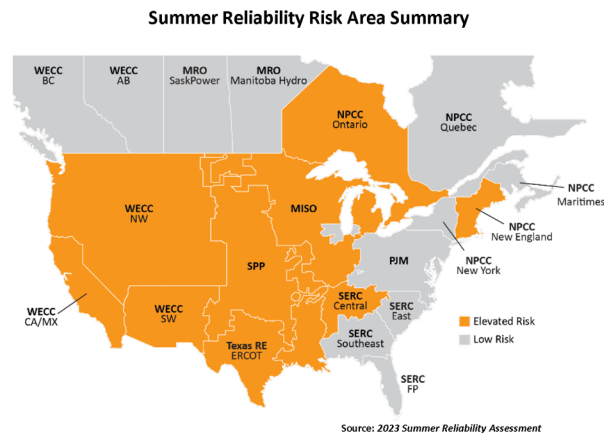
NERC's 2022 Long-Term Reliability Assessment³ (LTRA) examines future reliability risk over a ten-year horizon. The LTRA finds numerous regions are at risk of energy shortfalls during normal peak conditions and during extreme conditions over the next five years. Factors that contribute to this risk include (1) retirements of flexible, dispatchable resources where their capacity, energy production, and essential reliability services have yet to be fully replaced, (2) extreme weather driven by a changing climate coupled with a generation resource portfolio that has grown more sensitive to extreme weather, and (3) limited addition of interstate electric transmission and fuel delivery infrastructure.



² NERC, 2021 ERO Reliability Risk Priorities Report (July 2021), https://www.nerc.com/comm/RISC/Documents/RISC%20ERO%20Priorities%20Report_Final_RISC_Approved_July_8_2021_Board_Submitted_Copy.pdf.

³ NERC, 2022 Long-Term Reliability Assessment (December 2022), https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2022.pdf.

The risk outlook for the upcoming summer is also concerning. NERC's *2023 Summer Reliability Assessment*⁴ reviews the energy outlook for the upcoming summer season, showing a step change in the risk environment. Among positive findings, the below risk map shows improvement over previous years in that there are no areas at risk of energy shortfalls during *normal summer conditions*. Increased deployments of wind, solar, and batteries positively impact resource adequacy. However, the map shows growing contagion of orange areas compared to previous summer assessments. In these areas, during extreme above-normal heat, long duration conditions, there is a ten percent chance of energy shortfalls occurring.



NERC Actions to Address Risks

To address the myriad challenges for BPS reliability, NERC has developed a comprehensive risk framework to guide the ERO in the prioritization of risks and provide guidance on the application of ERO policies, procedures, and programs to inform resource allocation and project prioritization. Certain key actions are described below.

Inverter-Based Resource Strategy

The speed of IBR resource deployment continues to challenge grid planners, operators, protection engineers, and many other facets of the electricity sector. Implemented correctly, inverter technology can provide significant benefits for the BPS. However, the new technology can introduce significant risks if not integrated properly. In *2022 State of Reliability*, NERC finds that large assessment areas have become dependent upon renewable resources to meet peak loads, but multiple events resulting in the loss of significant amounts of solar resources in Texas

⁴ NERC, *2023 Summer Reliability Assessment* (May 2023), https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_SRA_2023.pdf.

and California confirm that unaddressed inverter interconnection and performance issues increased reliability risk.⁵ The *2021 Long-Term Reliability Assessment*⁶ projects a rapid growth of IBRs – mostly wind, solar photovoltaic (PV), battery energy storage systems, and hybrid plants – with projections of nameplate capacity for solar PV projects in all development stages exceeding 500 GW over the next 10 years. NERC has developed an IBR mitigation strategy comprised of specific activities under four core tenets: Risk analysis, interconnection process improvements, best practices and education, and new standards to govern the planning and operations of IBRs.⁷ NERC is also revising its rules to ensure that a greater portion of IBRs are subject to such standards and fall within the nation’s regime for a reliable bulk power system.

Energy Assessments

Historically, analyses of energy available to the bulk electric system focused on capacity reserve levels across peak-demand time periods. Energy availability and essential reliability services were assumed to be a direct result of this certain capacity. The variability of renewable generation, demand volatility, the need for sufficient flexibility from balancing generation resources, and the potential for natural gas supply interruptions all create uncertainty in the system’s ability to provide energy and essential reliability services needed for reliable operation. Recent events, including Winter Storm Uri, have highlighted the need for energy reliability assessments that analyze all hours of a given study period rather than just the peak hours.

After undertaking extensive industry stakeholder engagement, NERC’s Energy Reliability Assessment Task Force initiated two Standard Authorization Requests (SARs) which were endorsed by the Reliability Security Technical Committee (RSTC) to mitigate this risk through energy assessments with corrective action plans. Various regulatory jurisdictions then would assess these plans for implementation or modification. The SARs, which are working through the NERC Reliability Standards process, would require Reliability Coordinators and Balancing Authorities to conduct energy assessments needed to evaluate energy requirements in their regions. One SAR would require energy assessments for the long term planning horizon (1 to 5 years), with corrective actions plans toward ensuring sufficient amounts of energy are available for a select set of scenarios.⁸ The second SAR is for operational planning (1 year or less), with energy surveys and actions that can be taken to ensure sufficient amount of energy reserves are available to meet energy requirements.⁹ Subject to the standards development process, review

⁵ NERC, *2022 State of Reliability* (July 2022),

https://www.nerc.com/pa/RAPA/PA/Performance%20Analysis%20DL/NERC_SOR_2022.pdf.

⁶ NERC, *2021 Long-Term Reliability Assessment* (Dec. 2021),

https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2021.pdf.

⁷ NERC, *Quick Reference Guide: Inverter-Based Resource Activities and Strategy* (March 2023),

https://www.nerc.com/pa/Documents/IBR_Quick%20Reference%20Guide.pdf.

⁸ SAR, “Energy Assessments with Energy-Constrained Resources in the Planning Time Horizon,” (June 8, 2022),

<https://www.nerc.com/pa/Stand/Project202203EnergyAssurancewithEnergyConstrainedR/2022-03%20Constrained%20Resources%20in%20the%20Planning%20Time%20Horizon%20Standard%20Authorization%20Request.pdf>.

⁹ SAR, “Energy Assessments with Energy-Constrained Resources in the Operations and Operations Planning Time Horizons,” (June 8, 2022),

<https://www.nerc.com/pa/Stand/Project202203EnergyAssurancewithEnergyConstrainedR/2022-03%20Constrained%20Resources%20in%20the%20Operations%20and%20Operations%20Planning%20Time%20Horizons%20Standard%20Authorization%20Request.pdf>.

and approval by the NERC Board and FERC, these new requirements will provide important planning tools to help assure energy availability.

Cold Weather Reliability Standards and Planning

FERC recently approved enhancements to Reliability Standards that address numerous recommendations identified in the FERC/NERC/Regional Entity Joint Inquiry Report that pinpointed lessons learned from the Winter Storm Uri arctic cold front event that affected Texas and the South Central United States in February 2021. The standards also build upon NERC's prior work, further advancing reliability through improved operations, generator cold weather preparedness requirements, and enhanced situation awareness between generators and reliability coordinators and balancing authorities. New and enhanced Reliability Standards address important activities such as cold weather preparedness planning, training requirements, freeze protection measures, and load shedding procedures. A separate joint inquiry is currently ongoing concerning Winter Storm Elliott that affected parts of the Southeast around the Christmas holiday last year. Upon conclusion of the inquiry, NERC intends to act expeditiously on recommendations. Finally, on May 15, 2023, NERC issued a Level 3 "Essential Actions to Industry" Alert urging immediate action and requiring industry to report to NERC on cold weather preparations for next winter.

Expanded Analytics and Modeling

NERC is undertaking a number of initiatives to improve analytics and modeling necessary to support grid transformation in a reliable way. Transmission Planners and Planning Coordinators are concerned about the lack of accurate modeling data and the need to perform more sophisticated studies during the interconnection process and long-term planning horizon. In many ways, the growth of inverter technology has pushed conventional planning tools to their limits, elevating a need for good models required to conduct more detailed studies using electromagnetic transient (EMT) models to address inverter-based resource integration issues. EMT studies have been used since the mid-1970s, and are now needed for studying possible reliability issues related to the interconnection of inverter-based resources. NERC is currently working on Reliability Standards proposing to include EMT models and studies in planning-related NERC Reliability Standards to ensure reliable operation of the BPS.

The NERC Inverter-based Resource Performance Task Force (IRPTF, now the Inverter-based Resource Performance Subcommittee or IRPS) undertook an effort to perform a comprehensive review of all NERC Reliability Standards to determine if there were any potential gaps or improvements. The IRPTF identified several issues as part of this effort and documented its findings and recommendations in the "IRPTF Review of NERC Reliability Standards White Paper."¹⁰ This project includes potential revisions to a number of NERC modeling standards to require, among other things, Generator Owners to provide verified dynamic models to their Transmission Planner for the purposes of power system planning studies. In addition, the IRPTF

¹⁰ NERC IRPTF, "IRPTF Review of NERC Reliability Standards" (Mar. 2022), https://www.nerc.com/comm/PC/InverterBased%20Resource%20Performance%20Task%20Force%20IRPT/Review_of_NERC_Reliability_Standards_White_Paper.pdf.

recommended revisions to clarify the applicable requirements for synchronous generators and IBRs.

Findings and Recommendations

Managing the pace of change is the central challenge for reliability. The rapid evolution of the generation resource mix is altering the operational characteristics of the grid. Through the transition:

- Until energy, capacity, and essential reliability services are fully replaced, the retirement of traditional units must be managed. This may require a new pricing construct to ensure that necessary reliability investments (e.g., winterization investments, costs to firm up fuel supply, etc.) are adequately compensated for in the competitive markets.
- It is imperative to understand and plan for the different operating characteristics of variable, inverter-based resources and take steps to ensure they contribute to reliability.
- The reliability attributes of all resources, especially fuel security and provision of essential reliability services, must be recognized and valued by the marketplace.
- Interagency coordination is absolutely needed for policies that impact generation, especially coal resources, to keep reliability at the forefront of the policy table.

More transmission and natural gas infrastructure is required to improve the resilience of the electric grid. Whatever approaches may ultimately be pursued, few long-haul transmission lines and pipelines are actually being planned and built. With construction scheduled to begin this summer, the current major project being developed in the desert Southwest underwent sixteen years of development and permitting. And the New England Clean Energy Connect project has resumed production after being halted through a ballot initiative in Maine. Despite these siting and permitting challenges, it is absolutely clear that:

- Electric transmission investment must keep pace with the increase in utility scale wind and solar resources, which are generally located outside of major load centers. Transmission investments can also strengthen the ability to transport power to different load centers, improving resilience through redundancy. Many are discussing the merits of a national transmission system similar to the interstate highway system, point-to-point DC lines, and other interconnections.
- Additional pipeline infrastructure (including gas storage to provide needed in-market flexibility) is needed to reliably serve load and enable natural gas to perform and even expand its role as a balancing resource.

Natural gas is essential to a reliable transition. Natural gas will remain essential to reliability for total energy and as a balancing resource. In many areas, natural gas-fueled generation is needed to meet energy demand during shoulder periods between times of high and low renewable energy availability, and to set frequency needed by IBRs until advanced grid forming inverters are in place coupled with energy storage. And on a daily basis in areas with significant solar generation, the natural gas fleet is a flexible generation resource to fill the gap. The criticality of natural gas as the “fuel that keeps the lights on” will remain until very large-scale and long

duration battery deployments are feasible or an alternative flexible fuel such as hydrogen, or small nuclear reactors can be developed and deployed at scale.

Regulation and oversight of natural gas supply for electric generation needs to be rethought. – While natural gas is key to supporting a reliable transformation of the grid, the natural gas system is not built and regulated to serve the needs of an electric power sector that is increasingly dependent upon reliable natural gas service. As it relates to BPS reliability, clear regulatory authority is needed over natural gas when used for electric generation. As seen in Storm Uri, the interdependence between the electric and natural gas sectors are increasing, and therefore the interface between these two energy subsectors require common practices on how to plan and operate these systems to benefit, not reduce, their reliable operation.

Planning for widespread extreme weather. The BPS must remain reliable and resilient during all operating conditions. As the recent extreme weather events show, industry should proactively plan for and recover from rare but expected events. Through event analysis, reliability assessments and Reliability Standards, and NERC Alerts, NERC is identifying and attempting to address these risks within our jurisdictional authorities. Regulatory and market structures need to support this planning, prioritize reliability, and support necessary investments.

Resource adequacy (capacity) does not guarantee energy sufficiency. We must shift focus to 24x7 energy planning, not just capacity plus a reserve margin. A diverse generation portfolio strengthens reliability and resilience, yet the benefits of diversity are lost when all resources underperform or fail. All generation sources have energy limits and physical constraints, and these limits and constraints need to be accurately accounted for in seasonal and long-term planning assessments.

Energy storage can and will be a game changer. As the technology continues to develop and economics continue to support the growing penetration of energy storage, these resources will become a game changer. However, we have to appreciate the gap that currently exists and the scale that we need to obtain. Investment in energy storage technologies and/or a hydrogen production and delivery systems will be required to achieve a largely or completely decarbonized electric system. Namely, a full system approach is needed to support the clean energy systems of the future.

Market Issues. While electricity market issues are outside of NERC’s direct purview, policymakers, planners, and market operators need to understand how electricity market policies value reliability and incentivize investments in hardening energy infrastructure.

Conclusion

Bulk power system reliability is at an inflection point. NERC assessments demonstrate that the electric grid is operating ever closer to the edge where reliability is at risk – an edge characterized by the prospect of more frequent and more serious disruptions that threaten human wellbeing and economic productivity. To be clear, NERC believes that the energy transformation can be

navigated in a reliable way. To do so, reliability must be anchored as our north star guiding the journey, with flexibility for course corrections that are surely needed for such a highly complex endeavor. The challenge is not whether we have the resources and technical ability to achieve a clean energy future. Rather, the central challenge is calibrating the pace of change with the reliability needs of a transforming system that must remain reliable and resilient at all times and under all conditions. As it exists today, this balance is out of calibration and must be corrected.

As the Electric Reliability Organization for the United States, NERC is exercising its full range of tools to support a highly reliable and secure North American bulk power system. The transmission system is indeed highly reliable, yet the aggregate electric system is threatened by a deteriorating risk profile. NERC's technical work is key to identifying risks and informing reliability actions identified in this testimony. NERC actively communicates risks to industry stakeholders, regulators, and policymakers, and develops additional regulatory measures to help address risks. With reliability as the central focus, solutions are found in coordination among jurisdictions, industry collaboration, and exploration of new authorities where needed. NERC is fully engaged in these endeavors and remains deeply committed to our work with this committee, industry stakeholders, and all policymakers to navigate this journey together.

The CHAIRMAN. Thank you, sir.
Mr. Asthana.

**STATEMENT OF MANU ASTHANA, PRESIDENT AND CHIEF
EXECUTIVE OFFICER, PJM INTERCONNECTION, L.L.C.**

Mr. ASTHANA. Chairman Manchin, Ranking Member Barrasso, and members of the Committee, good morning and thank you for the opportunity to participate in this hearing.

I am the CEO of PJM Interconnection. PJM was formed in 1927 and has grown to become the largest grid operator in the U.S. We direct the operation of the grid in all or parts of 13 states and DC, serving 65 million customers. PJM does not have a profit motive. We are revenue-neutral and independent of our members. Our primary purpose is maintaining the reliability of the bulk power system, and this is a responsibility we take very seriously. Like most of the country, our grid is in transition. And to give you a sense of scale, our peak load is about 150 gigawatts. Our interconnection queue has over 250 gigawatts of generation waiting to be processed to see if they can interconnect reliably. Ninety-seven percent of this generation is solar, wind, batteries, or some hybrid of these resources.

And so, looking at our queue, it is very clear that transition is happening, and PJM is committed to facilitating it as reliably and cost-effectively as possible, using the power of competitive power markets. And we have taken significant steps already toward this goal, including major interconnection reform, which is expected to result in the processing of over 200 gigawatts of new generation over the next few years. We have also launched an initiative called Ensuring a Reliable Energy Transition, to bring all of our work under a single umbrella. PJM is currently in a sound position. If you look at the chart that you showed, Senator Manchin, we, today, have sufficient generation to meet the anticipated needs of our system, and our markets and our planning and our operations add between \$3 and \$4 billion of value of savings a year to the customers in our footprint.

However, as we look further out, we are concerned by four trends. And they are very similar to the trends that Jim laid out, but the four trends are: number one, the dispatchable generation we rely upon today to balance the grid is retiring and it is retiring at a rapid rate and it is retiring mostly driven by policy considerations. Second, electrification and large-scale data center construction is poised to create significant load growth in our footprint. Third, our new generation queue is largely intermittent, and so we need multiple megawatts of the new generation to replace one megawatt of the retiring generation. And finally, the new generation is coming online slower than anticipated, and there are a lot of reasons for this, and we can talk about it. But if these trends continue, we see increasing resource adequacy risk in the future.

And these issues are not just a concern for us. We have seen the NERC chart that shows two-thirds of the country is already at risk of elevated resource adequacy risk as soon as this summer. So we believe it is critical to take steps now to de-risk the transition. The math of it is straightforward, even if the execution is not. We need to accelerate the pace of new entry through actions such as permit-

ting reform, further interconnection reform, and policies that reduce backlog in the supply chain. And while most new entry is likely to be renewable plus batteries, given the composition of our queue, we will also need new natural gas resources. And so, whatever we do, we need to be able to enable those and the infrastructure that supports them.

Additionally, we will need to slow down the retirement or restriction of existing generation until replacement capacity is deployed and operational at scale and demonstrated to be doing so. And frankly, we see this as the single largest risk in the energy transition. It is not about the entry of the new intermittent resources, it is about the premature exit of the resources that we need to balance the grid. Finally, we strongly encourage an approach to policymaking that expressly evaluates reliability impacts in the development phase of policy, not after the fact. And we stand ready to help with this evaluation and to play our part to ensure a reliable transition. And like Jim, we are optimistic that it is possible, but also, we feel it will take a different approach to policymaking that prioritizes reliability in it.

Thank you very much for the opportunity to present my testimony today and for your attention to these important issues. I look forward to your questions.

[The prepared statement of Mr. Asthana follows:]



UNITED STATES SENATE COMMITTEE ON ENERGY & NATURAL RESOURCES

Testimony of Manu Asthana
President and CEO, PJM Interconnection
June 1, 2023

For Public Use



Executive Summary

Chairman Manchin, Ranking Member Barrasso, and members of the Committee: Thank you for the invitation to participate in this hearing and share PJM's perspective on the reliability, resilience and affordability of the bulk power system.

Based in Valley Forge, Pennsylvania, PJM Interconnection operates as the "air traffic controller" of the electric grid, ensuring the reliable flow of power to 65 million customers in all or parts of 13 states and the District of Columbia. Additionally, PJM plans necessary enhancements to the grid to ensure reliability into the future, and operates electricity markets within its region to competitively procure capacity and to efficiently dispatch generation to meet load in real time.

My testimony today addresses PJM's perspectives on the reliability and resilience of the bulk power system and makes six key points. In summary:

- **The U.S. electric grid is experiencing an accelerating transition toward the use of intermittent renewable generation.** This transition is primarily driven by local, state and federal policies, combined with consumer decisions, aimed at mitigating the critical risk posed by climate change. This transition is evident in PJM's interconnection queue, where we currently have more than 250,000 MW of generation to be studied for interconnection, 97% of which is either renewable or batteries or a hybrid of both.
- **PJM has sufficient generation to meet the needs of our system today. However, as we look further out, we are concerned by the trends we see.** Specifically, the generation fueled by fossil fuels (mostly coal and natural gas) that we rely upon to balance the grid is retiring at a significant rate. Electrification of the transportation, industrial and building sectors is poised to create material load growth. Our region is also experiencing significant data center construction, which is creating major pockets on the system of increasing demand. New generation in the queue is largely intermittent, so we need multiple megawatts to replace one megawatt of retiring generation. And, new generation is coming online slower than anticipated. If these trends continue, our models show increased risk of having insufficient resources later in this decade to maintain the reliable electric service that consumers expect.
- **This is not a concern unique to the PJM grid.** Indeed, as the North American Electric Reliability Corporation's (NERC) recent summer assessment shows, roughly two-thirds of the U.S. (but not the PJM region) already faces increased resource adequacy risk this summer.¹
- **Industry and policymakers can take steps now to de-risk the transition.** These steps include implementation of policies that accelerate the pace of new generation and transmission entry, such as permitting reform, further interconnection reform and policies that reduce backlog in the supply chain. They also include adoption of policies that slow down the retirement or restriction of existing generation until replacement generation is deployed and operational at scale. We also encourage an approach to policymaking that expressly considers reliability impacts in the development phase of the policy and not after the fact.

¹ [2023 Summer Reliability Assessment](#), North American Electric Reliability Corporation, May 2023.



- **Competition at the wholesale electricity level has been embodied in the law since passage of the Energy Policy Act of 1992. At PJM, we have used the power of competition to reinforce short- and long-term grid reliability** by using market signals to incentivize both investment in new generation and replacement of older, less efficient generation. These efficiencies result in \$3.2 billion to \$4 billion in annual value to customers and significantly enhanced reliability, which is vital to the region. Competitive markets are a proven tool that can deliver a more efficient energy transition.
- **PJM embraces its role to help reliably facilitate this industry transition while using competitive markets to drive efficiencies.** We have already taken significant steps toward this goal, including interconnection queue reform which is expected to result in the processing of over 200,000 MW of new generation requests in the next three years, deployment of the State Agreement Approach to facilitate 7,500 MW of offshore wind in New Jersey, and coordination with state and federal governments on maintaining system reliability while developing and implementing their specific energy policies. We, our members and stakeholders continue to work on additional steps toward this goal, which currently include and/or will include efforts to further accelerate the interconnection of new generation, enhance our forward-looking transmission planning process, and appropriately value the reliability attributes needed to support a system that is more reliant on just-in-time fuel resources. PJM is also launching an initiative to bring all of its activities targeted at ensuring a reliable transition under a single umbrella.²

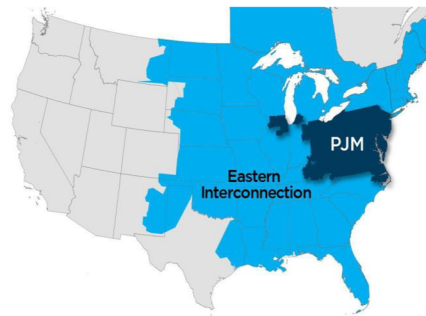
² See PJM's [Ensuring a Reliable Energy Transition](#) web page at PJM.com.



The Role of PJM

PJM ensures the reliable flow of power to all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and Washington, D.C., as shown in **Figure 1**. As such, we are responsible for ensuring reliable and efficient delivery of electricity over the bulk electric system to one-fifth of the nation. We are fuel-neutral in carrying out this function, valuing resources using different fuel types based on their reliability value and cost-effectiveness.

Figure 1. PJM Service Territory



The PJM grid consists of 88,115 miles of transmission lines and approximately 1,400 generation sources of all types, including coal, natural gas, nuclear, wind, solar, batteries and hydro facilities, along with more than 500 demand response and energy efficiency resources. We are interconnected with our neighboring systems in the Eastern Interconnection, which geographically includes over two-thirds of the United States and Canada. As a regional transmission organization (known as an RTO), PJM delivers power from the high-voltage transmission grid to local distribution utilities, who then are responsible for the delivery of power to end-use customers. We are independent of the various market participants and do not profit from any particular type of resource.



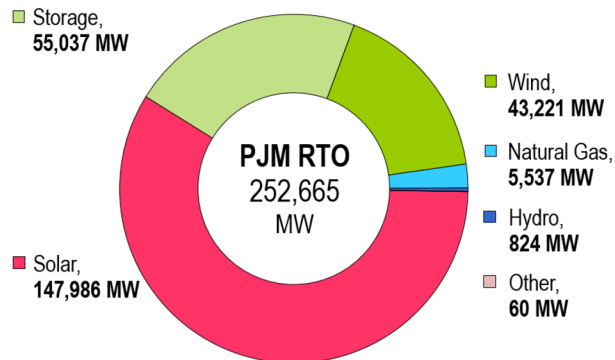
Testimony

Experiencing an Accelerating Transition Toward Intermittent Renewable Generation

As with the entire U.S. electric grid, PJM is experiencing an accelerating transition toward intermittent renewable generation. Policies, economics and consumer choices are shifting the grid away from dispatchable, emitting-generation resources toward intermittent generation with little-to-no carbon emissions. A look at PJM's interconnection queue for new generation requesting access to the transmission system is evidence that we are, in fact, in a transition. As generation retires, the PJM queue represents immediate options for replacement.

New requests to connect to the PJM grid are almost exclusively – approximately 97% – coming from renewable resources and batteries, including 59% solar resources and 17% wind resources, as shown in **Figure 2**. An additional 22% of interconnection requests are from storage resources, which are mostly lithium ion batteries co-located at the site of the aforementioned solar or wind resources under study.

Figure 2. PJM Queued Capacity (Nameplate as of April 1, 2023)



Sufficient Generation Exists Today; Current Trends Raise Concerns Further Out

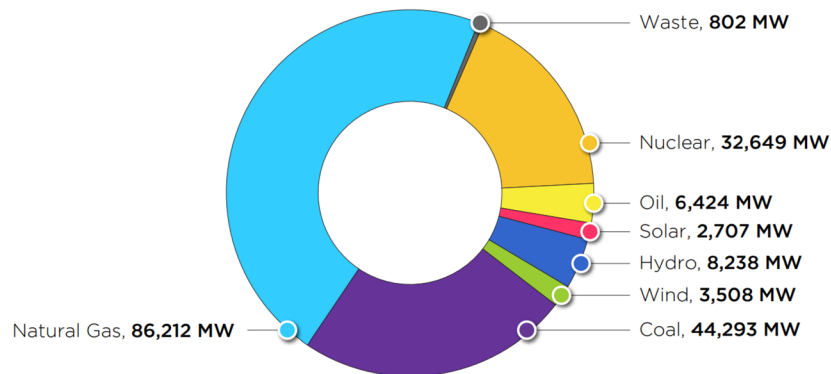
The PJM fuel mix is balanced and diversified between different fuel types, as shown in **Figure 3** below, and we have adequate generation resources to serve the anticipated needs of our system today. Indeed, NERC in its 2023 Summer Assessment represented the PJM region as one of the regions in the country projected to have adequate reserves for this summer.



However, as we look further out, maintaining an adequate level of generation resources, with the right operational and physical characteristics, will be essential for PJM's ability to reliably serve electrical demand through the energy transition. Our recent analysis observed the following four trends that, in the collective, increase the risk that we may have difficulty maintaining such an adequate level of generation resources with the necessary attributes over time.

- 1| The rate of electricity demand is likely to continue to increase from electrification and increasing deployment of high-demand data centers in the region.
- 2| Dispatchable generators are retiring at a rapid, date-certain pace largely due to government and private sector policies.
- 3| Replacement generation is primarily intermittent and limited-duration resources, requiring multiple megawatts of these resources to replace one megawatt of dispatchable generation.
- 4| Retirements are at risk of outpacing the construction of new resources, due to a combination of industry forces, including siting and supply chain, whose long-term impacts are not fully known.

Figure 3. PJM Existing Installed Capacity (Nameplate as of Dec. 31, 2022)





The pace of retirements is being driven in large part by state laws and federal environmental initiatives that create a clear near-term, date-certain requirement for generation to comply or retire. On the other hand, the pace of additions of new renewable generation is currently slower than anticipated.³ We are hopeful that the technological development of longer-duration batteries and other storage technologies that can address the challenges created by a large fleet of intermittent generation will create new grid management tools, but timing of commercial availability of these tools is uncertain.

This analysis is further detailed in our most recent paper in the Energy Transition in PJM series.⁴ This analysis clearly highlights our concern that, if current trends continue, we will be at elevated risk of resource adequacy shortfalls later in this decade. However, we believe this risk is avoidable through policies that accelerate the rate of entry of new generation (such as through permitting reform) and stop or slow down the exit of traditional thermal generation we currently use to balance the grid until replacement generation is installed and operating at the required scale.

The reliability challenge from prematurely losing resources we need to manage a grid dominated by intermittent renewable generation is concerning. Identifying this possible outcome now affords us an opportunity to manage this transition in an orderly and coordinated fashion that ensures the continued supply of reliable electric power.

To the industry's credit, we have managed energy transitions before, such as the fleet turnover driven by the shale gas revolution and the U.S. Environmental Protection Agency's Mercury and Air Toxics Standard Rule issued in December 2011. However, the current energy transition to a cleaner and greener fleet is much larger and affects virtually every aspect of energy supply and delivery.

³ There are a number of reasons for a lag in development of new resources. The large increase in renewable generation project development has led to rapidly expanding interconnection queues across the U.S., increasing the time it takes for a project to be approved for interconnection to the grid. Developers report delays with project siting and permitting combined with significant supply chain backlogs. This is a multifactorial problem that will require solutions to each of the barriers to new generation development.

I am pleased that we have underway a significant reform of the interconnection process targeted at moving new projects through our interconnection process much more rapidly. This process will clear the existing interconnection backlog by moving from a "first-come/first-served" paradigm to a "first-ready/first-served" paradigm. The transition to this new interconnection process will begin this summer.

Concerningly, we are finding that even projects that have completed our interconnection queue are still not undertaking construction at an adequate rate. For example, in 2022, we had only 2,000 MW of projects get built, of which only 700 MW were renewables, when there were over 30,000 MW of generation with signed interconnection agreements. Today, we currently have about 44,000 MW of projects that have come through our study process with either signed or pending final agreement and should be moving to construction; that should grow to about 62,000 MW by year's end. And thus far in 2023, we recently had a 1,900 MW combined-cycle gas plant come online, but we have seen only 250 MW of renewable generation start up this year.

⁴ Energy Transition in PJM: [Resource Retirements, Replacements and Risks](#) (PDF), Feb. 24, 2023.



If the rate of premature retirements continues to outpace the installation of replacement generation with the attributes necessary to maintain grid reliability, the nation may well face challenges with maintaining adequate supply to meet electric power demand, at the very time we are moving aggressively to electrify the transportation and home heating sectors. On the other hand, if we proactively address these challenges now, I believe we can achieve an orderly and coordinated transition that ensures the continued supply of reliable electric power.

Steps Industry and Policymakers Can Take Now To De-Risk the Transition

Potential Areas for Action – PJM

PJM is working with its members and stakeholders on several initiatives focused on ensuring a reliable transition, including:

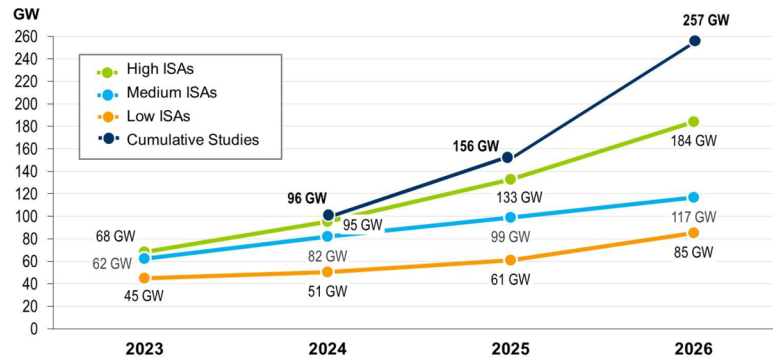
- Implementing interconnection process reform that was recently approved by FERC and is expected to significantly accelerate interconnection queue throughput, as shown in **Figure 4** below. PJM will also consider additional potential interconnection policy reforms with its members.
- Calibrating our reliability risk modeling and capacity market rules and generator requirements to the changing needs of the grid as we go through this transition.
- Continuing to support state policies through creative and innovative solutions, such as cooperative planning between PJM and states to meet their public policy needs under PJM's State Agreement Approach. By way of example, we recently planned targeted transmission projects with the state of New Jersey to support their offshore wind policy goals.
- Working with FERC as well as the gas pipeline industry to improve the coordination of the natural gas and electricity markets.

To capture these actions in a central location, PJM is launching an initiative to bring all of its activities targeted at [Ensuring a Reliable Energy Transition](#) under a single umbrella, as stated in the body of this testimony.

Figure 4 shows PJM's current estimates for the total capacity of interconnection studies (in gigawatts) that will be completed through 2026 and high, medium and low scenarios for projects expected to have completed all necessary studies to ensure reliability of the grid, including signed interconnection service agreements, in the same time frame.



Figure 4. Study Projection



Potential Areas for Action – Congress

PJM cannot address these issues alone. Because policies at the state and federal level are a key factor in driving the disparate pace of retirements and replacements, the solutions require a coordinated approach to effectuating the transition. Along these lines, our conclusions and recommendation are as follows:

- Supply chain issues are plaguing many different segments of the industry, ranging from shortages of transformers to solar panels. The Inflation Reduction Act creates important incentives that will help to spur domestic manufacturing of these critical components of electricity supply and delivery. Until that domestic manufacturing develops, we will need to ensure that new federal and state policies across agencies are coordinated to take into account whether the particular policy initiative is helpful in addressing these immediate infrastructure needs.
- There is a critical need for integrating analysis of the reliability impact of specific state and federal policies prior to those policies being adopted. We remain concerned that compliance dates that impact the generation fleet are being chosen without such a rigorous analysis always being undertaken. Although EPA does undertake a limited analysis in certain rulemakings, its analysis does not take into account the reliability attributes needed by system operators or the feasibility and cost of the compliance alternatives proposed in the particular rulemaking. From a process standpoint, it would be appropriate for a more thorough reliability analysis to become a standing requirement for federal actions that could impact reliability. And although EPA has entered into a Memorandum of Understanding with the Department of Energy to consider reliability issues as part of EPA rulemaking deliberations, the reliability analysis and consultation should be undertaken with those entities that actually operate the grid in addition to, and not as a replacement for, coordination with DOE.
- Instead of date-certain "retire or comply" policies or policies that limit generator output on a fixed, pre-determined date, policies should tie such retirement signals or generator output restrictions to the demonstration that adequate replacement capacity is installed and operating. Currently, the nation is developing environmental and reliability policy in separate silos with limited and not very transparent



coordination between the environmental and reliability regulators. Increased coordination and synchronization of the nation's environmental and reliability needs may require discrete changes to the statutes governing each agency's mission to embrace this effort. But the time may be ripe to initiate these statutory changes so that each regulator has both the authority and ability to develop policies that harmonize and meet both the nation's reliability and environmental goals.

- We are cognizant of the Committee's interest in permitting reform. We agree that balanced reform in this area is needed. By the same token, we are becoming increasingly dependent on natural gas. Additional pipelines will need to be sited to meet our reliability needs. Also, EPA's greenhouse gas proposal calls for a vast increase in co-firing of natural gas or hydrogen, or sequestration of carbon dioxide; if the rule stands, a new transportation network for hydrogen and a transportation and storage network for carbon dioxide will need to be sited, permitted and built. For all these reasons, we would ask that permitting reforms undertaken include an element that would ensure timely permitting of infrastructure needed to maintain and enhance reliability of the electric grid.
- Finally, the electric grid is one of our most important infrastructure assets. It is critical to both the economy, health and security of all Americans. We need to give protection and enhancement of the grid the same level of focus that we give to our equally important environmental goals. Policies need to continually be crafted in a manner that ensures that the reliability and affordability of the grid can be maintained and enhanced as we transition to a cleaner and greener generation fleet.

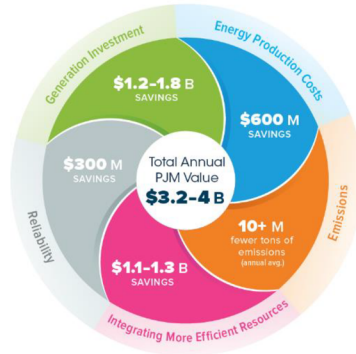
Proven Benefits: Using Markets and Competition To Reinforce Grid Reliability

PJM's markets exist to reinforce grid reliability by ensuring that market signals work in tandem with regional reliability requirements and those of the North American Electric Reliability Corporation (NERC). For example, our capacity market is designed to procure resources available to meet projected peak demand and other contingencies three years ahead of time. Through our Day-Ahead and Real-Time energy markets, we produce a security constrained economic dispatch across our footprint, ensuring that the most efficient and cost-effective mix of resources is called on each hour of each day to achieve reliability at the least cost to customers. In addition, based on economics and needs, in any given hour, we either export excess power supplies to our neighbors or import power from those neighbors. This helps to support reliable and cost-effective operations throughout the entire Eastern Interconnection.

The efficiencies of this market-based approach to reliability have resulted in real savings to customers. We have examined those savings, which we categorize into the following segments reflected in **Figure 5**.



Figure 5. PJM Value Proposition



Of late there have been, in some quarters, attacks on the use of competitive markets as a tool to ensure reliability. Congress set the country on a path toward the development of competitive markets through the work of this very Committee in crafting the Energy Policy Act of 1992. As demonstrated above and in countless independent economic analyses, that choice has proven to be a success in ensuring a more reliable and cost-effective grid. You don't have to take my word for it – the benefits of the competitive market model have been analyzed and proven over and over again.

I want to highlight this quote from a letter from the Clean Energy Buyers Association (CEBA), a diverse set of over 350 energy customers, including nearly one-fifth of the Fortune 500:

*"Organized wholesale electricity markets (OWMs) are fundamental to advancing CEBA's vision and goals. By leveraging the power of competition and balancing clean energy generation over large geographic regions, OWMs produce billions of dollars in benefits annually. These markets expand purchasing options and support reliable clean energy integration..."*⁵

We have seen this same recognition from those on both sides of the aisle who have served as FERC commissioners. A bipartisan group of former FERC commissioners wrote to FERC in June 2021, stating:

⁵ [Organized Wholesale Electricity Markets](#), [Clean Energy Buyers Association](#) website.



*"As former FERC Commissioners and Chairs, appointed by both Republican and Democratic Presidents over the past three decades, we are united in our strongly held view that organized regional wholesale power markets, known as RTOs and ISOs, provide compelling platforms for renewable energy development and are achieving considerable consumer benefit."*⁶

The market has opened up opportunities for the export of electricity from resource-rich states like West Virginia, Ohio, Pennsylvania and Indiana to net-consuming states. This results in economic development and consumer cost savings on both sides of the transaction. The market has also allowed for the development of innovative and promising new technologies being deployed in our footprint, ranging from batteries to Smart Wires technology to opportunities for customers to receive the value of their rooftop solar devices in the market. And retail customers can receive the benefit of some or all of this activity at the wholesale level. Depending on the rules established by the state utility commission, the revenues received by utilities from the export of power from resource-rich states are credited back to customers in those states through their electric bills. Competitive markets are a proven tool that can deliver a more efficient energy transition.

Conclusion

The PJM system as it stands today is a reliable system with an adequate capacity reserve margin. Despite PJM's healthy reserve margins, however, recent winter storms (Uri 2021, Elliott 2022) have provided a sobering reminder of the critical role that resource adequacy will play through the energy transition. Further, for the first time in recent history, PJM could be at risk of facing resource adequacy challenges should these trends – high load growth, increasing rates of generator retirements, and slower entry of new resources – continue. This situation is not unique to the PJM system – roughly two-thirds of North America is rated by NERC at being at elevated resource adequacy risk this summer.

This risk is not a forgone conclusion. Rather, we believe a reliable energy transition is achievable through policies that accelerate the rate of entry of new generation and stop or slow down the exit of traditional thermal generation we currently use to balance the grid, until replacement generation is installed and operating at the required scale. We at PJM are working on a range of initiatives to help achieve a reliable transition. In our judgment, a reliable transition will also require policy changes aimed at accelerating new generation entry and slowing exits. We stand ready to roll up our sleeves and work with all of you on these challenging questions.

I thank you for the opportunity to present my testimony today. I look forward to any questions you may have.

⁶ [Letter of Nine Former Federal Energy Regulatory Commissioners and Chairs to FERC Re: Organized Wholesale Power Markets](#) (PDF), June 2, 2021.

The CHAIRMAN. Thank you so much.
Dr. Lott, please.

STATEMENT OF DR. MELISSA C. LOTT, SENIOR RESEARCH SCHOLAR AND DIRECTOR OF RESEARCH, COLUMBIA CENTER ON GLOBAL ENERGY POLICY, COLUMBIA UNIVERSITY SCHOOL OF INTERNATIONAL AND PUBLIC AFFAIRS

Dr. LOTT. Good morning, Chairman Manchin, Ranking Member Barrasso, and members of the Committee. Thank you for the invitation to speak with you today.

My name is Melissa Lott, and I am the Director of Research and a Senior Research Scholar at Columbia University's Center on Global Energy Policy, which is a part of the School of International and Public Affairs. I am also an adjunct professor at Columbia University's Climate School, and I have worked as an energy systems engineer for nearly 20 years across the United States, as well as in Europe and Asia. Today, in the different positions that I hold, I also serve in roles at the United Nations Council of Engineers for the Energy Transition, which is an independent advisory council to the U.N. Secretary General, and I serve as a member of the World Economic Forum's Global Future Council on the Future of Economics of Equitable Transition.

My testimony today will cover three broad things. One, the impacts of reliability issues on health and the economy in the United States. The second is the broad determinants of grid reliability, including the effects from different fuel sources and technologies in the context of the evolving supply mix. I will also discuss actions the Federal Government could take to support a reliable and affordable electricity system in the face of a changing climate, evolving demand for electricity, and also the integration of these new supply technologies.

Electricity is a vital input to the U.S. economy. It supplies around 22 percent of total final energy consumption in the numbers we look at from 2020. And while net generation has remained essentially flat since 2005, the mix of technologies providing that electricity in the U.S. has changed significantly over that period. And there are expectations that competitive pricing, existing incentives, and commitments from many states and territories will lead to reductions in the use of existing unabated coal and gas power plants while promoting even more growth from renewables and potentially nuclear power and fossil fuel plants that are fitted with carbon capture technologies. And while the mix of supply technologies is changing significantly, so is the demand for electricity, particularly from personal vehicles, from heating and cooling, and from cooking. While the exact pathway that we are going to take over the coming decades is difficult to predict, a substantial increase in electricity demand is all but certain when we look at the numbers.

This increased demand on the electricity sector will make reliability and affordability even more vital. In 2021, U.S. customers experienced an average of seven hours without power, and this figure is significantly higher than some other comparable economies. And it looks even more dramatic when we dive in and look at the variation between states. So customers in Louisiana, for example,

experienced over 80 hours without power. Customers in Oregon experienced losses of over 25 hours. And those in Texas, my home state, were without power for 20 hours. The American Society of Civil Engineers gave the U.S. energy system a C-minus grade in their latest assessment, and they identify severe weather as the predominant cause of outages.

When we look at access to reliable, affordable, and clean energy, we see it as a major determinant of health, well-being, and economic prosperity. Extreme weather events, which are increasingly likely to come in the coming decades, strain underprepared power systems when people need them the most. Extreme heat increases the need for air conditioning, and home heating is even more vital in the middle of extreme winter storms. During winter blackouts, people seek alternative fuel sources such as charcoal, which has led to accidental deaths due to carbon monoxide poisoning. And when we look at access to health care, it is also hampered during power outages in extreme weather, leaving people with elevated health needs particularly vulnerable. And the economic effects of electricity outages are also severe. Estimates put the wider economic impact of Winter Storm Uri at upwards of \$300 billion—just one example. More recently, Congress has provided leadership in supporting critical investment in clean energy innovation and infrastructure deployment in the Energy Act of 2020, the Infrastructure Investment and Jobs Act, the CHIPS and Science Act, and the Inflation Reduction Act. And today, Congress has the opportunity to provide transformative leadership to ensure that the future electricity grid can support the delivery of reliable, affordable, and clean electricity to households and businesses around the country.

In my written testimony, I outlined a number of recommendations for Congress to consider, and I will highlight three here. One is strengthening the requirements for risk assessments and mitigation planning in power and sector planning processes. So coupling up something I talk about, which is energy systems models and climate models, so we are planning for the future and not for the past. The second is reforming environmental review and permitting processes for projects across the entire electricity sector, and I say that intentionally—the entire sector—so supply, the grid, the whole thing. And the third one that I will highlight is finding ways to better utilize existing infrastructure and rights-of-way to accelerate projects that can provide near-term benefits. I provide more details on these topics and all recommendations in my written testimony.

Again, I would like to thank the Committee for holding this hearing on the reliability and resiliency of electricity in the United States in light of these recent reliability assessments and alerts. The investments that we have made over the past 50 years have created an energy system that supports our health and well-being and our economy, and the investments that we make moving forward are vital. Thank you again for inviting me to be a part of this important discussion.

[The prepared statement of Dr. Lott follows:]



Center on
Global Energy Policy
at COLUMBIA | SIPA



CONGRESSIONAL TESTIMONY OF
DR. MELISSA C. LOTT
DIRECTOR OF RESEARCH AND SENIOR RESEARCH SCHOLAR
CENTER ON GLOBAL ENERGY POLICY
SCHOOL OF INTERNATIONAL AND PUBLIC AFFAIRS
COLUMBIA UNIVERSITY

June 1, 2023

BEFORE A HEARING OF THE SENATE COMMITTEE ON ENERGY AND NATURAL
RESOURCES, UNITED STATES SENATE, 1ST SESSION, 118TH CONGRESS

Good morning Chairman Manchin, Ranking Member Barrasso, and members of the Committee. Thank you for the invitation to speak with you today.

My name is Melissa Lott. I am the Director of Research and a Senior Research Scholar at the Center on Global Energy Policy, which is a part of the School of International and Public Affairs at Columbia University in New York. I am also an Adjunct Professor at Columbia University's Climate School. I have worked as an energy systems engineer and advisor for nearly 20 years in the United States, Europe, and Asia at organizations including the Asia Pacific Energy Research Center, the International Energy Agency, and as a Presidential Management Fellow in the U.S. Department of Energy.

I joined Columbia University three and a half years ago, in the fall of 2019. In addition to my roles at Columbia, since 2022, I have served on the United Nations Council of Engineers for the Energy Transition (CEET), which is an independent advisory council to the U.N. Secretary-General. I am also a member of the World Economic Forum's Global Future Council on the Future of Economics of Equitable Transition.

My testimony today will first cover the impacts of reliability issues on health and the economy in the United States. Second, I will discuss the broad determinants of grid reliability, including the effects of different fuel sources and technologies in the context of an evolving energy supply mix. Lastly, I will cover actions that the federal government could take to support a reliable and affordable electricity system in the face of a changing climate, evolving demand for electricity, and the integration of new electricity supply technologies.



The U.S. Electricity Mix is Poised to Use More Electricity, New Technologies

Electricity is already a vital part of the U.S. economy, and the role of the electricity sector is expected to grow. Furthermore, the mix of technologies used to produce this electricity is expected to change at a rapid pace moving forward. As discussed below, two key trends underpin this change. First, a need to increase investment in the electricity sector to support reliable access to affordable and clean electricity. Second, a necessity to adopt new tools to support the power sector's transformation to clean supply technologies.

Today, electricity accounts for just under a quarter (22.3%) of energy end-use¹. Net electricity generation grew tenfold to 4 terawatt-hour per year (TWh/year) between 1952 and 2005, before flattening out². However, while generation has remained essentially flat since 2005, the mix of technologies supplying electricity in the United States has changed significantly.

Our electricity sector has been decarbonizing and is expected to continue this trend for the next 30 years³. Several factors have driven the decarbonization of electricity. Cheap natural gas supplies resulting from advanced hydraulic fracturing and directional drilling techniques have led to significant coal-to-gas switching. Price declines in solar, wind, and energy storage technologies have spurred their adoption across the country. Incentives for the production of renewable energy exist in many states⁴. A significant number (24) of states and territories - representing 52% of the U.S. population - have adopted targets either to decarbonize their power sector and/or decarbonize their entire energy sector by at least 2050⁵. Some states have much more ambitious near-term targets. For example, New Jersey plans to achieve 100% clean electricity by 2035 to support its goal of achieving a net-zero energy sector by 2050⁶. If met, these targets, will radically shift the electricity supply mix away from fossil fuel sources, towards wind, solar, geothermal, and nuclear power. Net-zero ambitions will also increase demand for

¹ <https://www.iea.org/countries/united-states>

² <https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T07.01#/?f=M&start=200001>

³ <https://www.eia.gov/totalenergy/data/browser/index.php?tbl=T07.02A#/?f=A&start=1949&end=2022&charted=1-2-3-5-8-14-15-13-12>

⁴ <https://www.dsireusa.org/>

⁵ <https://www.cesa.org/projects/100-clean-energy-collaborative/guide/map-and-timelines-of-100-clean-energy-states/>

⁶ <https://www.nj.gov/governor/news/news/562023/20230215b.shtml#:~:text=Achieving%20100%25%20clean%20electricity%20by,the%20Natural%20Resources%20Defense%20Council.>

electricity. Various net-zero pathways see net electricity generation grow from around 4 TWh per year in 2020 to between 5 to 16 TWh/year in 2050⁷.

On the demand side, nearly two-fifths (39%, 1.42 TWh/year⁸) of electricity that is used in the United States is consumed in residential buildings for space heating and cooling, water heating, and other uses (e.g., for electric appliances). Just over one-third (35%, 1.37 TWh/year⁹) of electricity is used by the commercial sector, primarily in commercial buildings. The industrial sector represents around one quarter (26%, 1.01 TWh/year¹⁰) of electricity use. In addition, a small fraction (around 0.2%, 0.01 TWh/year¹¹) of electricity is currently used in the transportation sector, primarily for public transit.

While the future remains uncertain, it seems very likely that electricity generation and consumption will only increase due to a number of factors, including increased electrification across all sectors. For example, the electrification of home heating systems is being incentivized across 15 states, with four states setting explicit deployment targets, targeting 12 million new heat pumps installed by 2030¹². In fact, electric heat pumps outsold natural gas heaters in 2022 in the U.S. for the first time.¹³ Demand for electricity for transportation is also projected to increase. For example, the growth of electric vehicle sales is expected to further increase electricity use both in buildings (e.g., through home charging in residential buildings) and through a network of charging stations. First quarter 2023 sales of electric vehicles exceeded 7% of all new vehicle sales¹⁴. Seventeen states have already adopted zero-emission vehicle (ZEV) standards and clean car standards that are likely to further accelerate the adoption of electric vehicles¹⁵.

Major Weather Events are Major Contributors to Blackouts

Access to reliable, affordable, and clean electricity is a major hallmark of a healthy and prosperous society. As electricity use in the U.S. economy increases, so does the

⁷<https://www.energypolicy.columbia.edu/publications/electrification-path-net-zero-comparison-studies-examining-opportunities-and-barriers-united-states/#1>

⁸<https://www.eia.gov/energyexplained/electricity/use-of-electricity.php#:~:text=Total%20U.S.%20electricity%20end%2Duse,3.4%25%20higher%20than%20in%202021.>

⁹ ibid

¹⁰ ibid

¹¹ ibid

¹² <https://rmi.org/millions-of-us-homes-are-installing-heat-pumps-will-it-be-enough/>

¹³ <https://www.canarymedia.com/articles/heat-pumps/chart-americans-bought-more-heat-pumps-than-gas-furnaces-last-year>

¹⁴ <https://www.coxautoinc.com/market-insights/q1-2023-ev-sales/>

¹⁵ <https://theicct.org/wp-content/uploads/2022/02/clean-car-infographic-feb22.pdf>



importance of ensuring the reliability and affordability of the electricity system, especially as the increasing frequency and severity of extreme weather negatively impact energy infrastructure.

In designing a system that is fit for purpose, it is crucial to understand the different causes of power outages that customers experience to design policies that can successfully address these issues. Power outages generally fall into two main buckets: power loss caused by extreme weather and those caused by lack of generation. In giving U.S. energy system a C- grade in their latest assessment, the American Society of Civil Engineers identifies severe weather as the predominant cause of customer outages¹⁶. Outages associated with supply-side failures are far less common, but recent infamous examples such as in Storms Uri and Elliott, have pointed out the cold weather vulnerabilities of some conventional power plants and their fuel sources.

Impacts of Blackouts on Health and the Economy

In 2021, the average electricity customer in the United States experienced 7 hours without power. But this number hides the significant variability between states and customer types, as well as the difference between loss of transmission or distribution lines or outages caused by loss of generation. It also does not show how often customers are asked to voluntarily reduce their demand in response to tight grid conditions. In 2021, customers in Louisiana experienced over 80 hours without power, Oregon 25 hours and Texas 20 hours on average¹⁷.

In February 2021, Winter Storm Uri resulted in multiple blackouts in the United States, particularly in Texas, where 4.5 million homes - approximately 12 million people - lost power for an average of 42 hours¹⁸. Some rural residents lost power for more than 10 days¹⁹. The loss of power also left almost half of Texans without access to potable water and the ability to boil available water²⁰. A report for the Public Utility Commission of Texas by researchers at the University of Texas at Austin²¹ concluded that the storm, while not of record-breaking severity, led to the worst loss of power across the state in terms of number and generation capacity outages. The study found that while no single generator type failure was fully responsible, the largest capacity outages were due to freezing natural gas plants and fuel supply disruptions. Inaccurate weather forecasting, inadequate weatherization of plants and limited natural gas storage ahead of the storm

¹⁶ <https://infrastructurereportcard.org/cat-item/energy-infrastructure/>

¹⁷ <https://www.eia.gov/todayinenergy/detail.php?id=54639>

¹⁸ <https://uh.edu/hobby/winter2021/>

¹⁹ <https://www.tpr.org/texas/2021-02-23/rural-hill-country-power-outage-texas-storm-ctec>

²⁰ <https://awwa.onlinelibrary.wiley.com/doi/abs/10.1002/awwa.1919>

²¹ <https://energy.utexas.edu/sites/default/files/UTAustin%20%282021%29%20EventsFebruary2021TexasBlackout%2020210714.pdf>



were also listed as contributing factors. The storm left at least 246 people dead in Texas alone²².

Winter Storm Uri was not wholly unprecedented²³. However, the severity of the impacts of the storm were compounded by a failure to learn from previous storms. Following the 2011 Groundhog Day blizzard, FERC issued a winterization recommendation to mitigate the impact of future winter storms²⁴. While FERC has begun implementing mandatory weatherization standards for some generators, FERC rules don't address the weatherization of natural gas wells or other portions of the fuel supply infrastructure that can also fail and take a plant offline²⁵.

The health impacts of an extended loss of power can be severe. Extreme weather events, which are increasingly likely in the coming decades, will further strain underprepared power systems precisely at the time when reliance on electricity is growing. Home heating is vital during winter storms. During winter blackouts, some are forced to seek alternative fuel sources such as cooking charcoal or running small generators indoors which can lead to accidental carbon monoxide poisoning²⁶.

Further, access to healthcare is limited during power outages²⁷. People with elevated health needs requiring medical equipment, such as those using at home ventilators, are some of the most vulnerable when the power goes out. Pregnant women face an increased risk of complications during outages²⁸, with low-income, uninsured individuals hit the hardest. In the aftermath of outages, those who can afford them often purchase batteries or backup fossil fuel generators which worsen local air pollution during outages. Low-income families and those who rent housing generally have a lower capacity to prepare for the next power outage and the physical and emotional strain of surviving an environmental disaster can persist for decades²⁹.

Power outages cost U.S. businesses, on average, about \$150 billion per year.³⁰ During Winter Storm Uri, Samsung's giant microchip factory in Austin was forced to shut down

²² <https://www.texastribune.org/2022/01/02/texas-winter-storm-final-death-toll-246/>

²³ <https://iopscience.iop.org/article/10.1088/1748-9326/ac0278/pdf>

²⁴ <https://www.ferc.gov/sites/default/files/2020-04/08-16-11-report.pdf>

²⁵ <https://www.ferc.gov/news-events/news/presentation-order-approve-proposed-reliability-standards-eop-011-3-and-eop-012-0>

²⁶ <https://www.worldscientific.com/doi/epdf/10.1142/S2345737621500226>

²⁷ <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7749027/>

²⁸ <https://www.sciencedirect.com/science/article/abs/pii/S0048969721004277>

²⁹ <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7967478/#:~:text=Elevated%20symptoms%20of%20PTSD%2C%20depression,Hurricane%20Katrina%20survivors%20%5B84%5D>

³⁰ <https://www.pewtrusts.org/en/research-and-analysis/reports/2015/10/americas-electric-grid-growing-cleaner-cheaper-and-stronger>



for over a month, leading to tens of millions of dollars of economic losses³¹. The broader economic impact of the storms of February 2021 has been estimated at upwards of \$300 billion³². Outages lead to increased insurance claims, diminished business confidence, and reduced growth. Between 2003 and 2012, estimates put the cost of weather-related outages on the U.S. economy between \$18 billion and \$33 billion per year³³.

What Recommendations Could the Federal Government Consider?

Much of the U.S. regulatory framework for the electricity sector is overseen by state legislatures and public utility or service commissions. However, the federal government can take steps to support a more reliable and affordable electricity sector as climate-change-related disasters are poised to increase. As my former colleague John MacWilliams stated in his testimony in 2020 before the House Committee on Energy and Commerce³⁴, congressional action has been taken before in the wake of reliability issues. For example, after the Northeast Blackout of 2003, Congress enacted the Energy Policy Act of 2005, which both strengthened the North American Electric Reliability Corporation (NERC) reliability requirements and granted the FERC greater ability to levy penalties for non-compliance with those standards³⁵. More recently, Congress provided leadership in supporting critical investment in clean energy innovation and infrastructure deployment with the Energy Act of 2020, the Infrastructure Investment and Jobs Act (IIJA), CHIPS and Science Act, and the Inflation Reduction Act.

Today, Congress has the opportunity to provide the leadership to ensure that a future electricity grid can support the delivery of reliable, affordable, and clean electricity to households and businesses around the country. There are a number of actions that the federal government could consider taking across the entire electricity sector outside of policy changes to power supply. New policies to improve the transmission grid and demand-side resources are crucial to ensuring that future Americans access power to support their lives and livelihoods.

³¹ <https://www.bizjournals.com/austin/news/2021/03/30/samsung-austin-semiconductor-is-back-online.html>

³² <https://www.texasce.org/wp-content/uploads/2022/02/Reliability-Resilience-in-the-Balance-REPORT.pdf>

³³ <https://www.energy.gov/articles/economic-benefits-increasing-electric-grid-resilience-weather-outages>

³⁴ CONGRESSIONAL TESTIMONY OF JOHN J. MACWILLIAMS BEFORE A JOINT HEARING OF THE COMMITTEE ON ENERGY AND COMMERCE SUBCOMMITTEE ON ENERGY AND SUBCOMMITTEE ON ENVIRONMENT AND CLIMATE CHANGE, UNITED STATES HOUSE OF REPRESENTATIVES 1ST SESSION, 116TH CONGRESS. January 28, 2020.

https://www.energypolicy.columbia.edu/sites/default/files/file-uploads/JohnMacWilliams-Testimony_CGEP_Commentary_012720-3.pdf

³⁵ https://www.nytimes.com/2008/08/14/nyregion/14blackout.html?_r=1&oref=slogin



First, Congress could consider strengthening communication networks to more effectively provide information to those affected by blackouts. Information such as the expected duration of a blackout and how to stay safe are critical to protecting human health and minimizing damage from reliability events. This critical information could include: where to access support services if safely sheltering in place is not an option; what to do to protect infrastructure in a person's home; and other emergency-related information (e.g., boil water notices). While the first goal should be to minimize the frequency and duration of blackouts, these networks can help to minimize damage when blackouts occur.

Second, Congress could consider strengthening requirements for risk assessment and mitigation planning in power sector planning processes. Ideally, this policy would require power sector planning processes to consider changing climatic conditions (e.g., temperature and rainfall patterns) and increased electrification of the United States economy. For example, an ongoing partnership between the New York Power Authority (NYPA) and Argonne National Laboratory³⁶ is leveraging currently available climate and infrastructure modeling techniques to help utilities better assess how extreme weather and other hazards may affect their assets and business. These modeling techniques can also help utilities understand how demand patterns might change given changing weather patterns. These assessments - along with lessons learned from previous reliability events - can directly feed into risk mitigation plans to help ensure a more reliable and affordable electricity system in the midst of an already changing climate. Planning and risk mitigation processes should extend beyond the electricity infrastructure and include the fuel delivery infrastructure as well.

Third, Congress could consider reforming environmental review and permitting processes for projects across the entire electricity sector (e.g., supply, transmission grid). The amount of investment that is needed across the electricity sector in the United States to support a reliable and affordable electricity supply will be substantial over the next few decades.³⁷ But investors that want to pursue energy infrastructure projects are currently hindered by slow and uncertain environmental review and permitting processes.

³⁶ <https://www.canarymedia.com/articles/climate-crisis/supercomputer-forecasts-helping-utilities-prepare-for-climate-change-extreme-weather>

and

<https://www.anl.gov/article/argonne-new-york-power-authority-plan-for-the-future-in-a-changing-climate>

³⁷ <https://theconversation.com/the-old-dirty-creaky-us-electric-grid-would-cost-5-trillion-to-replace-where-should-infrastructure-spending-go-68290>

Recent congressional actions supporting critical investments in clean energy infrastructure deployment are encouraging, but without a clear process to enable permitting and siting of infrastructure projects, increased uncertainty surrounding decision timelines hinders progress, increases costs, and threatens the viability of needed projects. Simply put, without updating and clarifying these processes, the investment we need will not happen.

Existing authorities are not ideally suited to support these infrastructure investments. The Center on Global Energy Policy has previously published work in partnership with New York University's Institute for Policy Integrity on how to increase investment in the transmission grid using existing authorities³⁸. However, the authors highlighted in that publication, existing authorities are limited and require complex coordination amongst different agencies. Passing legislation that would streamline environmental review and permitting process timelines is crucial given the speed and scale of infrastructure investment needed to support a reliable, affordable, and clean electricity sector.

This recommendation does not suggest that all proposed projects should be rubber-stamped, but that decisions should be made in a transparent and timely manner.

Fourth, Congress could consider ways to better utilize existing infrastructure and rights-of-way to accelerate projects that can provide near-term benefits.

Investments are needed to both harden and expand the capacity of existing power lines as well as building new lines. These new lines can provide robust connections between new electricity supplies and growing demand centers. To achieve maximum benefits, efforts should target reducing total electricity demand growth (e.g., through increased minimum appliance energy standards and building energy efficiency) as well as demand side management technologies can help to reduce costs, reducing peak demand, and providing flexibility during extreme events (e.g., demand-response).

Furthermore, as discussed in work from the Center on Global Energy Policy, Congress has a tremendous opportunity to pave the way for the use of existing infrastructure (e.g., existing pipelines, roads) and other rights-of-way to support accelerated adoption and use of clean energy technologies. For example, having the Department of Transportation work with the Department of Energy to develop dual transport and energy infrastructure corridor standards that can be utilized across our nation's 160,000 miles of highways and 140,000 miles of railroads can accelerate the successful deployment of needed grid and pipeline infrastructure without establishing new rights-of-way in many cases.

³⁸ <https://www.energypolicy.columbia.edu/publications/building-new-grid-without-new-legislation-path-revitalizing-federal-transmission-authorities>



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Another tangible opportunity exists in utilizing existing power plant infrastructure to support new technologies and fuels. For example, simple cycle natural gas-fired power plants can be updated to transition to turbines that allow for fuel switching between natural gas and hydrogen. These flex-fuel plants could serve not only as a source of power during extreme events, but also as an energy storage resource.

Fifth, Congress could consider policies that support investment in a diverse set of supply-side technologies and necessary upstream systems. The U.S. electricity sector has already been decarbonizing and is expected to continue this trend for the next 30 years. In order to support a reliable, affordable, and clean electricity supply, it is important to ensure that policies support investment across low-carbon technologies including not only variable renewables, but also energy storage and firm, dispatchable power.

The Center on Global Energy Policy has published work showing that expanding the clean-electricity focus beyond variable renewable technologies to include other types of zero-carbon power—as well as investing in the transmission and distribution grid that delivers this power to communities around the country—will allow the U.S. to build a reliable, secure, and sustainable zero-carbon power system. Work at the Center on Energy Policy indicates that the most robust pathway to an affordable, reliable, and clean electricity sector includes a mix of technologies. These technologies fall into three main groups - variable renewables (e.g., solar, wind), energy storage technologies (e.g., batteries, hydrogen), and firm, dispatchable power plant technologies (e.g., nuclear, hydropower, geothermal, fossil fuel with carbon capture)³⁹.

Each of these individual technologies comes with tradeoffs. Natural gas wellheads, nuclear power plant water pumps, and wind turbine blades can all freeze. Cooling ponds or rivers for thermal power plants (e.g., coal, natural gas, and nuclear) can get too hot during heat waves, resulting in lower output from existing power plants. While we should take steps to mitigate against these impacts, our work shows that a more robust option is to also support the buildout of a diverse set of technologies that make catastrophic, cascading reliability issues an extremely low probability event.

The electricity markets under FERC's jurisdiction can help achieve this type of "all-of-the-above" supply mix. While some at FERC have suggested that we need to step away from competitive markets to make the clean energy transition work, I would instead suggest that Congress embrace competitive principles and direct FERC to develop technology-neutral markets that are designed to help states meet their clean energy

³⁹ <https://www.energypolicy.columbia.edu/publications/energy-transition-fact-sheet-pathways-100-clean-electricity>



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targets, up to and including, allowing states (on a voluntary basis) to specify the clean energy or carbon content of their energy mix.

Furthermore, policies should also consider the necessary upstream infrastructure and supply chains associated with new energy sources, such as pipelines to move hydrogen or captured carbon dioxide emissions.

Conclusion

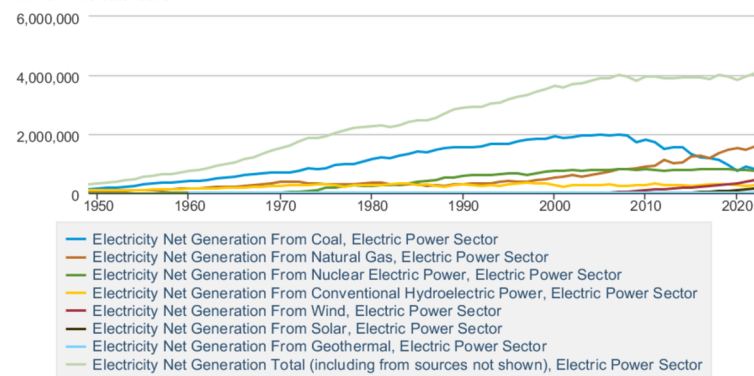
I would like to thank the Committee for holding this hearing on the reliability and resiliency of electricity in the United States in light of recent reliability assessments and alerts. Critical investments over the past 50 years have created an electricity system that supports not just our health and wellbeing, but also the wellbeing of our country's economy. However, the grid of the future will need to adapt to the demands of a different economy. The choices made today will set the course for how this system will evolve moving forward. These recent reliability events should be a call for action regarding the need to increase investment in the electricity (and its supporting) infrastructure to ensure a reliable, affordable, and clean electricity sector in the face of a changing climate. Streamlining the permitting process and accelerating the changes already underway in energy markets can help to accelerate the investments that are needed. Thank you again for inviting me to be a part of this important discussion.



Appendix

Table 7.2b Electricity Net Generation: Electric Power Sector

Million Kilowatthours

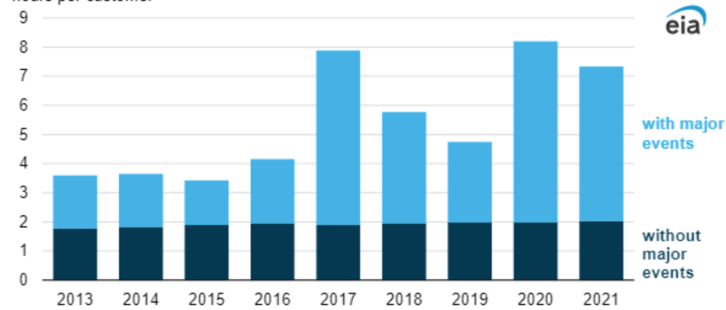


Data source: U.S. Energy Information Administration

<https://www.energypolicy.columbia.edu/publications/electrification-path-net-zero-comparison-studies-examining-opportunities-and-barriers-united-states/#1>

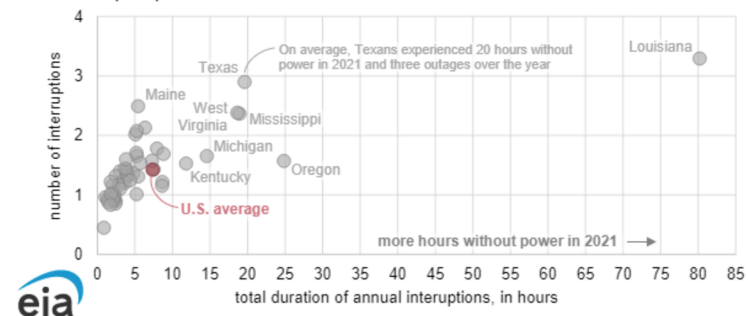


Average duration of total annual electric power interruptions, United States (2013–2021)
hours per customer



<https://www.eia.gov/todayinenergy/detail.php?id=54639>

Average total annual electric power interruption duration and frequency per customer, by U.S. state (2021)





Net Generator Outages and Derates by Fuel Type (MW)

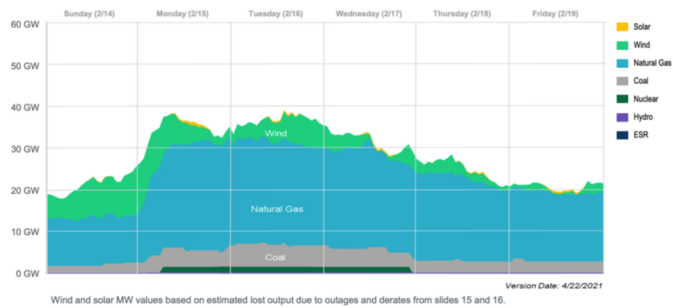
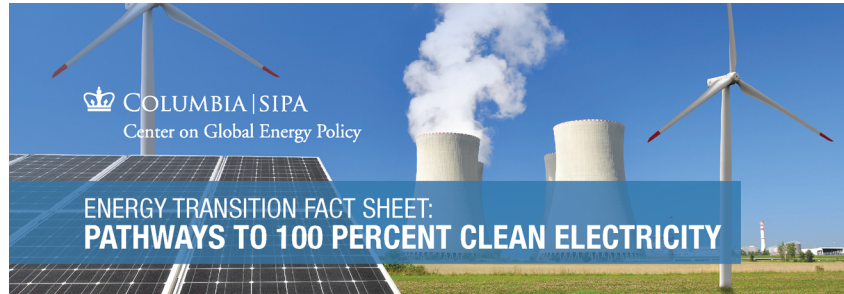


Figure 2.o. Net capacity outages and derates by fuel type, relative to expected contribution from wind and solar. Since wind and solar are not expected to generate at their nameplate capacity rating, the value derating shown here is less than that for wind and solar in Figure 2.n. Figure by ERCOT.⁵⁷



In order to decarbonize the US economy at a reasonable cost and on an accelerated timeline, the country needs to both grow and rapidly decarbonize the power sector. This process will require many new technologies that support an affordable, equitable, and achievable transition. Expanding the clean-electricity focus beyond variable renewable technologies to include other types of zero-carbon power—as well as investing in the transmission and distribution grid that delivers this power to communities around the country—will allow the US to build a reliable, secure, and sustainable zero-carbon power system.

Power Sector Emissions Are Falling, But Too Slowly

The power sector is currently responsible for nearly a third (32 percent) of total emissions from the US energy sector. Recent emissions reductions in the power sector have been driven primarily by fuel-switching from coal to natural gas and renewables. From 1990 to 2019, total power generation in the US increased by 36 percent.¹ Over the same period, coal-fired power generation fell from 52 percent (1,594 terawatt hours [TWh]) of total power generation to 23 percent (966 TWh), while natural gas's share of generation increased from 12 percent to 38 percent (373 TWh to 1,562 TWh), and renewables grew from 12 percent to 17 percent (357 TWh to 720 TWh). Due in large part to rapid shifts in the power sector, its annual carbon dioxide emissions peaked in 2007 in the United States and have since declined by 1.3 percent per year on average.² But emissions are still falling too slowly to meet the Paris Agreement's central aim to keep global temperature rise this century to "well below 2°C" above pre-industrial levels.

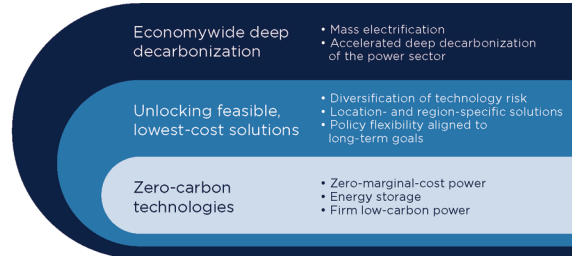
Three Technology Pillars of Deep Decarbonization

There is strong agreement in the literature³ that if the US is to achieve deep and economywide emissions reductions, the power sector should: 1) reduce emissions to nearly zero and 2) grow to support the electrification of other sectors such as transportation, space heating, and some industrial applications. The literature is similarly clear that the most affordable pathways to a reliable, zero-carbon power sector include a mix of technologies across three broad pillars:

1. **Zero-marginal-cost variable power plants** (e.g., wind, solar). These technologies have no fuel costs and are frequently the cheapest source of electricity in the system. But they are not always available and so need other technologies to ensure reliability.
2. **Firm, dispatchable zero-carbon power plants** (e.g., nuclear; hydro; and natural gas with carbon capture, utilization, and storage [CCUS]). These plants can provide electricity 24-7-365 in order to support the reliable supply of electricity to customers while keeping costs low.
3. **Energy storage technologies, including both short-duration** (e.g., batteries) **and long-duration** (e.g., zero-carbon hydrogen).

Analysis has shown⁴ that removing any of these three pillars leads to escalated costs and increased risk of implementation failure. For example, pathways that singularly pursue a goal of achieving 100 percent variable renewables (e.g., wind and solar) are likely to be materially more costly than diversified portfolios that also include firm, low-carbon generation (e.g., hydro, nuclear, natural gas with CCUS) and energy storage.





Policy Recommendations

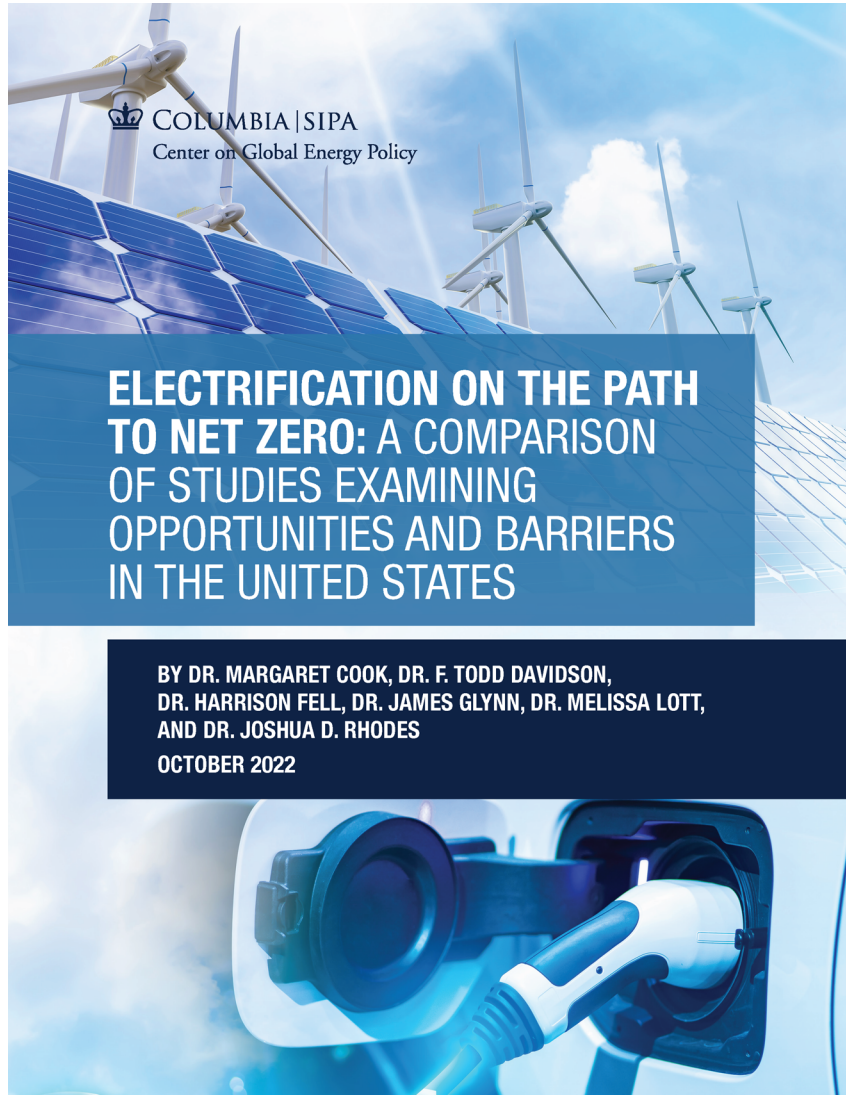
Policy makers seeking paths to accelerate the transition to zero-carbon electricity should emphasize the importance of all three technology pillars when choosing decarbonization targets and designing strategies to achieve them. Furthermore, policy makers can take the following concrete actions to support a rapid and affordable transition to zero-carbon power:

1. Keep existing zero-carbon technologies such as nuclear power plants and hydropower facilities operating for as long as possible.
2. Frame policies to support 100 percent zero-carbon power, including an array of zero-carbon technology options across the three technology pillars.
3. Support research, development, and deployment of new and improved zero-carbon technologies across the three technology pillars.
4. Support investments in the transmission and distribution grid to advance the efficient movement of zero-carbon electricity from power plants to communities.

Notes

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**ELECTRIFICATION ON THE PATH
TO NET ZERO: A COMPARISON
OF STUDIES EXAMINING
OPPORTUNITIES AND BARRIERS
IN THE UNITED STATES**

**BY DR. MARGARET COOK, DR. F. TODD DAVIDSON,
DR. HARRISON FELL, DR. JAMES GLYNN, DR. MELISSA LOTT,
AND DR. JOSHUA D. RHODES
OCTOBER 2022**

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5. the impact of local air pollution on equitable global decarbonization,
6. as well as the development of the first zero-carbon energy system pathways for Ireland consistent with the Paris Agreement.

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EXECUTIVE SUMMARY

There is a strong and growing consensus that a simultaneously growing and decarbonizing electricity sector is necessary to meet declining greenhouse gas emissions targets. Rallying cries to “electrify everything” have captured the focus of many headlines and policy forums in recent years. However, there are important questions that remain unanswered about the electrify everything movement, including the technical, social, and political feasibility of the approach, as well as the affordability and equitability of implementation. While reducing emissions is paramount in mitigating the negative impacts of the energy system to the environment and human health, it is also critical that changes to energy infrastructure are both socially and politically acceptable, as well as affordable to help ensure an economically vibrant future. These nuanced dynamics are not easily articulated in public forums regarding the goal to electrify everything. A more detailed assessment of the problem might discover a better path forward.

This report, part of the Power Sector and Renewables Research Initiative and Energy Systems Modeling Analytics program at Columbia University’s Center on Global Energy Policy, in conjunction with IdeaSmiths, examines eight recent major US studies on the topic. Six of the studies focus on strategies and pathways to a net-zero energy system and two assess the value of electrification and expanded transmission networks. This work serves to compare their assumptions and results. The authors’ purpose in analyzing the studies was threefold. First, the report explores the degrees of electrification in the United States that might be needed to achieve net-zero pathways as well as where and how electrification could occur under model assumptions. Second, it examines the relative roles of variable generation resources (e.g., wind and solar), energy storage (both short- and long-duration), and firm low-carbon power (e.g., natural gas with carbon capture, nuclear, hydro, and geothermal) in the energy transition to meet increasing levels of clean electricity demand. Finally, the report examines the barriers that could hinder both increased electrification and decarbonization of the pivotal power sector.

By examining and comparing the studies and scenarios within them, the authors were able to identify shared themes resulting in robust insights that can be useful in informing policy makers and guiding other decision-making processes. Broad recommendations across studies include: (1) decarbonizing electricity; (2) electrifying end uses; (3) lowering energy demand; and (4) increasing transmission, distribution, and energy storage infrastructure. Seven major barriers to expanding electrification include challenges around: (1) the pace of transition, (2) technology advancement, (3) infrastructure siting, (4) equipment cost, (5) supply chains, (6) human capital/jobs, and (7) public support.

To attain the various decarbonization goals analyzed in these studies, federal, state, and/or local regulators would need to implement an array of policies to accelerate the pace at which clean energy technologies are deployed. While the studies generally do not compare specific policies but rather the least-cost path(s) to achieving certain decarbonization targets, none of their reference scenarios indicate the energy sector will decarbonize fast enough to meet emissions targets without additional policies.



Other key findings regarding the potential for electrification in the United States drawn from the eight studies include the following:

- To meet the demands of an electrified economy, electricity generation will need to grow rapidly, up to four times current levels. Starting in 2020, current electricity generation levels of 3,900-4,300 terawatt-hours (TWh) will need to grow to between 5,000-16,000 TWh in 2050, depending on the degree of electrification and its sources.
- All studies indicate a future that heavily relies on renewable technologies such as wind and solar while reducing use of fossil fuels and phasing out coal by 2035. Of the five studies modeling scenarios out to 2050, wind and solar were expected to supply 43-91% of electricity generation, a 5- to 15-fold increase compared to today's levels.
- A wide mix of technologies will be needed to achieve deep decarbonization within the power sector. Pursuing a 100 percent variable renewable energy electricity system is likely to cost more than pursuing a diversified portfolio that also includes firm, low-carbon generation technologies such as geothermal and nuclear as well as various forms of energy storage (e.g., batteries, hydrogen, etc.).
- The studies' scenarios also rely on increased transmission and flexible demands to efficiently deploy renewable energy resources across time and space. The required scale of transmission expansion is significant: One study estimates that \$2.7 trillion in investment will be needed between 2020 and 2050, and another study assumes up to a 70 percent increase in total resource cost due, in part, to a 1,200 percent increase in transmission capacity over that currently installed.
- Despite the shift toward electrification, all studies include some continued use of some gaseous fuels, though the role of hydrogen and other synthetic gases varies greatly depending on assumptions.
- Multiple studies note that incentives for consumers of electric vehicles, heat pumps for space and water heating, and electric cooking could assist in increasing the pace of transition. In the highly electrified scenarios, the transportation sector sees rapid growth in EV sales across all vehicle classes, particularly light-duty vehicles. The same scenarios estimate that 100% of residential and commercial heating and cooking appliance sales need to be electric by between 2030 and 2040, and that by 2050, 95-100% of heating and cooking demand in the United States needs to be met by electricity.
- The studies find that some industry shifts to electrification due to efficiency gains, such as iron and steel making via electric arc-furnaces. However, for harder-to-electrify end uses such as freight, aviation, and other industry (e.g., cement, ammonia, hydrogen, biofuels, etc.), the studies favor the use of low-carbon fuels, increasing fuel efficiency, and pairing some end uses with carbon capture.

All of the studies examined in this report were completed prior to passage of the Inflation Reduction Act of 2022 (IRA). The IRA might shift the cost burden for different decarbonization solutions, but it does not invalidate the findings of the studies. While the IRA makes significant progress in addressing many challenges related to decarbonization, additional electrification hurdles will need to be overcome on the path to net-zero carbon emissions, as highlighted in this report.



CHAPTER 1: OVERVIEW OF MAJOR THEMES

To electrify many of the energy demands across the economy—a goal often considered vital to mitigating the negative impacts of climate change on human health and the environment while keeping energy affordable—the electricity sector must simultaneously grow and decarbonize. This report analyzes eight studies focused on the United States to explore the degree to which, as well as where and how, electrification might occur in net-zero pathways. It also examines relative roles of variable generation (VG) resources (e.g., wind and solar), energy storage (both short and long duration), and firm low-carbon power (e.g., natural gas with carbon capture use/storage, nuclear, hydro, geothermal) in the energy transition to meet increasing levels of electricity demand. The report concludes with recommendations based on its findings.

This analysis reviews six prominent studies that discuss strategies and pathways to achieve a net-zero energy system economy and two that focus on the value of electrification and expanded transmission networks. Table 1 and Table 2 provide a list of the studies and their scenarios considered in this report.

Table 1: Studies evaluated in this report

Study name	Abbreviation	Reference
Princeton's "Net-Zero America"	Princeton	Larson et al. 2020
"Carbon-Neutral Pathways for the United States"	Williams	Williams et al. 2021
Vibrant Clean Energy's "Zero by 2050"	VCE	Vibrant Clean Energy 2021
"The Long-Term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050"	White House	The White House 2021 (Global Change Assessment Model team)
Electric Power Research Institute's (EPRI) "Powering Decarbonization: Strategies for Net-Zero CO ₂ Emissions"	EPRI	Blanford et al. 2021
Berkeley's "2035 Electricity" and "2035 Transportation" reports	Berkeley 2035	Phadke et al. 2020; Baldwin et al. 2021
National Renewable Energy Laboratory's (NREL) "Electrification Futures Study"	EFS	Jadun et al. 2017; Hale et al. 2018; Mai et al. 2018; Sun et al. 2020; Murphy et al. 2021; Zhou and Mai 2021
NREL's "Interconnections Seam Study"	Seams	Bloom et al. 2021



Table 2: Study scenarios reviewed

Study abbreviation	Scenario	Description
Princeton	REF	Reference
Princeton	E+	High electrification
Princeton	E-	Less-high electrification
Princeton	E-B+	High biomass
Princeton	E+RE-	Renewable constrained
Princeton	E+RE+	100% renewable
Williams	Reference	Reference
Williams	Central case	High electrification
Williams	Low land	Land is constrained
Williams	Delayed electrification	Electrification is delayed
Williams	Low demand	Demand is constrained
Williams	100% renewable primary energy	100% renewable
Williams	Net negative	Carbon emissions are reduced beyond net zero to net negative
VCE	EBAU	Economic (not carbon constrained electricity sector) projections with electrified economy through 2050 (with distributed energy resources [DER], cooptimization, and novel tech)
VCE	EBAU-	Economic (not carbon constrained electricity sector) projections with electrified economy through 2050 (without DER co-optimization or novel tech)
VCE	ECE	100% clean economy by 2050 (with DER co-optimization and novel tech)
VCE	ECE-*	100% clean economy by 2050 (without DER co-optimization or novel tech but with expanded available variable renewable electricity [VRE] and storage buildout rates)
VCE	ECE HVDC	100% clean economy by 2050 (with DER co-optimization and novel tech and HVDC macrogrid by 2025)
VCE	ECE HVDC+	100% clean economy by 2050 and clean electricity by 2035 (with DER co-optimization and novel tech and HVDC macrogrid by 2025)
VCE	ECE HVDC-	100% clean economy by 2050 and clean electricity by 2035 (without novel tech and with HVDC macrogrid by 2025)

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Study abbreviation	Scenario	Description
VCE	ECE HVDC-*	100% clean economy by 2050 and clean electricity by 2035 (without novel tech and with HVDC macrogrid by 2025 but with expanded available VRE and storage buildout rates)
VCE	ECE HVDC--	100% clean economy by 2050 and clean electricity by 2035 (without DER co-optimization or novel tech and with HVDC macrogrid by 2025)
EPRI	Reference	Reference
EPRI	Net zero by 2050	Net-zero electricity sector by 2050
EPRI	100% renewable by 2050	100% renewable
Berkeley 2035	Baseline	Reference
Berkeley 2035	90% clean by 2035	Policy of 90% clean energy by 2035
EFS	Reference	Reference
EFS	Medium	Medium electrification
EFS	High	High electrification
Seams	Base Case	Reference
Seams	Design 1	Existing B2B facilities are replaced at their current (2017) capacity level and new air capture (AC) transmission and generation are co-optimized to minimize system-wide costs.
Seams	Design 2a	D2a: Existing B2B facilities are replaced at a capacity rating that is co-optimized along with other investments in AC transmission and generation.
Seams	Design 2b	D2b: Three HVDC transmission segments are built between the Eastern Interconnection and Western Interconnection, and existing B2B facilities are co-optimized with other investments in AC transmission and generation.
Seams	Design 3	D3: Macrogrid (a nationwide HVDC transmission network) is built, and additional AC transmission and generation are co-optimized to minimize system costs.

While each study differs in its approach, it was possible to compare general trends and assess similar scenarios across studies, including (1) the reference or business-as-usual (BAU) scenarios, (2) the main expanded electrification scenarios, (3) the increased renewable energy (RE) scenarios, and (4) the lowest cost scenarios. By examining and comparing the studies and scenarios shown in Table 1 and Table 2, respectively, this analysis was able to identify shared themes that appeared across studies, which could be useful in informing policy-making and other decision-making processes.



In general, the models used in these types of studies are seeking to develop the most cost-effective pathways toward their goals, such as decarbonization. Ideally, the models would include all forms of cost, including capital costs for construction of infrastructure, variable costs for maintaining and operating infrastructure, associated impacts from policies, including but not limited to tax credits, and the comprehensive assessment of indirect costs (e.g., road building and waste disposal), as well as externalities (e.g., emissions and impacts on biodiversity). However, the models are not comprehensive nor consistent in their treatment of costs. For example, to the authors' knowledge, the models do not account for every change within the economy that is required to enable changes in infrastructure (e.g., the cost of constructing new roads to install wind turbines or other large infrastructure at a greenfield site). The studies also do not consistently quantify the impacts of externalities related to infrastructure development (e.g., beyond the cost of carbon, what is the specific cost of potential biodiversity loss locally and globally as a result of choosing different pathways?). For example, the Regional Energy Deployment System (ReEDS) model used by Berkeley and NREL in EFS does not include environmental or health externalities. The Seams study states benefits/costs reported should be considered lower bounds as they do not reflect externalities. VCE does not consider social costs. Berkeley 2035 and Princeton both report social costs such as health impacts separately from the objective function (i.e., these costs do not affect model outcomes but are calculated for each scenario). EPRI considers a scenario with a price on carbon but not a social cost of carbon. This scenario is separate from the net-zero scenario analyzed in this report. Despite those limitations, the studies analyzed here represent some of the most holistic assessments of costs associated with modifying domestic energy infrastructure on a path to net-zero carbon emissions. A more detailed discussion of the methodologies used for assessing cost in each of the studies is provided in the System Costs section, including Table 3.

The different scenarios in each study are created by a combination of changing input prices that directly impact the pathways, such as the future cost of natural gas or solar photovoltaic (PV), and/or applying constraints that the model must adhere to as it develops a least-cost path forward, such as limits to transmission builds or binding carbon budgets. Much thought and effort go into the model inputs for each scenario because they seek to emulate real-world economic and societal constraints while charting the optimal path forward. The reader can examine the original studies to gain additional insight regarding what costs they do and do not include in their modeling scenarios and how assumptions are managed to alter the different scenarios.

The studies by Princeton, Williams et al., Vibrant Clean Energy, the White House, and EPRI (1–5) each explore pathways to achieve net zero by 2050. EPRI's study also evaluates additional pathways, including achieving net-zero electric sector emissions by 2035. The Berkeley 2035 Electricity and Transportation reports each evaluate one policy scenario: (a) achieving 90 percent clean electricity by 2035 and (b) achieving 100 percent electric light-duty vehicle (LDV) sales by 2030 and 100 percent electric medium-duty vehicle (MDV) and heavy-duty truck sales by 2035.

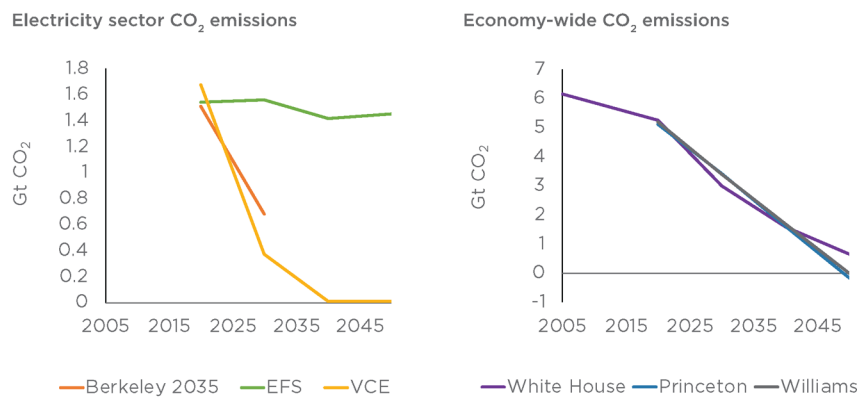
The Electrification Futures Study explores expanding demand-side electrification. Whereas the Interconnections Seams Study focuses on multiple transmission scenarios, including



expanding high-voltage direct current lines and creating a macrogrid across the nation. Both studies evaluate these changes against multiple generation profiles and constraints.

A summary of the pace of carbon emissions reductions modeled by the studies is shown in Figure 1.

Figure 1: Carbon reduction timelines across studies



Note: Economy-wide values are the White House average CO₂ emissions; Princeton E+, E-, E-B+, and E+RE- (E+RE+ is similar); and Williams Central Case, Delayed Electrification, Low Demand, and Low Land (Net Negative and 100% Renewable Primary Energy have further reductions). Electricity sector values include Berkeley 2035 (electricity), EFS High, and VCE ECE HVDC+ (clean economy and clean energy scenarios ECE HVDC-, ECE HVDC-, and ECE HVDC- have similar trajectories). The EFS study was an electrification study, not a net-zero study, so its electricity sector emissions were not required to get to zero carbon emissions by 2050.*

Consensus and Constraints of Electrification on a Path to Net Zero

Electrification Strategies on a Path to Net Zero

The studies evaluated indicate that expanding electrification on a path to net zero² is possible but challenging—no technology, policy, or behavioral change is sufficient on its own. The pathways explored in each of the studies suggest profound changes are needed across the economy to reach net zero and often touch on similar themes and recommendations, including the following:

- Reducing fossil fuel use, including eliminating coal generation by 2035.
- Replacing fossil fuels with carbon-free energy sources, mainly wind and solar. Some



scenarios within the studies also expand traditional or advanced nuclear, as well as hydro and geothermal.

- Deploying a diversified set of technologies is estimated to be the least-cost path toward reducing emissions in the electricity sector. These technologies include having firm, low-carbon power generation, such as natural gas with carbon capture and storage (CCS)/carbon capture, utilization, and storage (CCUS), nuclear, etc.
- Short- and long-term energy storage is considered important, although not a dominant requirement unless policies require 100 percent renewable electricity. Some of the modeled scenarios also include high blends of hydrogen (H₂) in gas turbines, wherein the hydrogen is produced from excess wind and solar and thus serves as a solution for long-term energy storage.
- Expanding transmission to enable increased electricity generation needs. Expanded renewable generation, particularly distributed generation, cannot satisfy future demands without adequate transmission. While transmission is expensive, a lack of transmission can cost more by leaving generation assets stranded or increasing congestion in electricity networks. Net-zero studies strive to optimize the location of transmission installations near locations with high levels of supply or demand. The Seams study further highlights that connecting the eastern and western grids may be a more economic national strategy than keeping them separate, with the objective of accessing higher quality resources, bridging climate zones, and mitigating the impact of regional, transient weather patterns.
- Increasing electrification of residential, commercial, industrial, and transportation sector end-use demands. The residential and commercial sectors must rapidly expand sales of heat pumps for space and water heating and electric resistance/induction for cooking to 100 percent of sales by 2030–2040. The transportation sector must rapidly expand electric vehicle (EV) sales in all vehicle classes. Light-duty electric vehicle sales should reach 100 percent of sales by 2040–2050 while electric medium- and heavy-duty trucks, which might also be fueled by hydrogen, need to reach 100 percent of sales by the same decade.
- Flexible demands that can shift consumption in time and/or space can help maintain the reliability of a grid that depends more on variable energy supplies.
- Reducing energy demand through efficiency and conservation with technology and infrastructure changes, such as improving a building exterior's thermal properties, will help enable greater adoption of electrification solutions because lower heating demand can be met by less power-intensive electric heat pumps. Increased industrial productivity via improved machinery or processes can also reduce the amount of energy required per manufactured unit. While not explicitly addressed in the studies, improved machinery or processes remains an important proxy for energy efficiency.

To deploy the significant clean energy capital and infrastructure needed to reach the various decarbonization goals analyzed in these studies, federal, state, and/or local regulators



would need to implement an array of policies. That is, none of the reference scenarios from these studies indicate the energy sector will decarbonize in a timely manner without additional policies.

Note also that the policies implemented to decarbonize the energy sector will ultimately determine the decarbonization path the US will take. Different types of energy policies have varying levels of economic efficiency in achieving decarbonization. For example, attempting to reach a decarbonized energy sector via tax rebates and subsidies will likely lead to a different set of investments than, say, a policy that decarbonizes through a clean energy standard or emissions tax. Similarly, the policies employed to encourage load reshaping and more general demand flexibility will determine the degree to which the demand side will electrify more energy services and accommodate more clean energy resources.

While the policies undertaken (or not) are key to determining the level and mechanisms of decarbonization, it is important to note that the studies explored here are generally not comparing policies needed to decarbonize but, again, are simply exploring the lowest cost path(s) to achieve certain decarbonization targets, subject to various technical and economic constraints.

Electrification Challenges

The decarbonization studies identify seven major challenges associated with expanding electrification: (1) the pace of transition, (2) technology advancements, (3) siting issues, (4) cost, (5) supply chains, (6) human capital/jobs, and (7) public support.

1. The starting point and pace for electrification and transition to clean electricity has a significant impact on the cumulative amount of carbon emitted. A slower pace and later start lead to more emissions. These changes are dependent on the mobilization of capital, including divestment and new investment decisions. Princeton notes that the biggest challenge here is scale and rate of infrastructure change.
2. A second constraint is the rate of technological advancements. Some studies rely on technologies that have not yet fully matured or declined in cost to be economically viable currently. The studies indicate that it is important to make progress in the maturation, scale, cost, and performance improvements in needed technologies, such as advanced nuclear (small modular reactors [SMRs] and molten salt reactors [MSRs]), advanced geothermal, carbon capture for power and industry, hydrogen production and combustion, ultracheap long-duration energy storage, synthesis of fuels, carbon-free alternatives for steel, high-yield bioenergy, and direct air capture. These advancements will be particularly important for sectors of the economy that will be harder to fully electrify, including aviation, heavy-duty vehicles (HDVs), and industrial applications that require high-temperature heat and chemical feedstocks.
3. A third constraint is siting. Restrictive siting requirements for transmission infrastructure and renewables facilities can constrain the feasible scale and pace at which the electricity sector can decarbonize. For example, siting delays for carbon storage can constrain the decarbonization of hard-to-abate industries or other



lingering fossil fuel uses.

4. A fourth constraint is cost. Most net-zero strategies are capital intensive at the system and individual levels, even if the lifetime costs are lower. Consumers may need assistance with the upfront cost of technologies integral to electrifying demand, such as heat pumps and electric vehicles. Economy-wide decarbonization studies that rely heavily on electrification estimate costs that range from \$2 trillion of clean energy investment to \$28 trillion in total system costs for an electrified net-zero economy (Berkeley 2035, VCE, and Princeton). More information is needed, though, to assess the total cost of achieving maximum electrification on a path to a net-zero economy. However, while these costs exceed the reference scenarios in the studies examined in this report, the benefits outweigh the additional costs across studies, in line with others such as those in the Intergovernmental Panel on Climate Change (IPCC) Sixth Assessment Report (AR6) Working Group III (WGIII) (Riahi et al. 2022).
5. A fifth constraint is the capacity of supply chains to rapidly develop for new industries and resiliently hold pace alongside a quickly electrifying economy. The geopolitical security of supply chains is increasingly important.
6. A sixth constraint is in the human capital and skill sets needed to fill the jobs required for a net-zero economy. The electricity supply sector needs skilled renewable energy and construction workers to make the transition. Similarly, the demand sectors will need technicians, manufacturing workers, and maintenance workers. It is also notable that there may be pockets of unemployment due to transition away from fossil fuels, indicating that a sector of the workforce would benefit from targeted reskilling to reduce some of the acute social costs of the transition.
7. Finally, a lack of public support can constrain the ability to transition to a clean energy economy. Public support is required for land use changes, for the uptake of electrifying technologies, and for many of the needed policy changes required to reach net zero. Such changes include redirecting fossil fuel subsidies to low-carbon technologies and streamlining clean infrastructure permitting. Historically, tax credits, such as the production tax credit and investment tax credit (ITC), have played a role in incentivizing the development of wind and solar. Similar policies may be required to sustain and accelerate development of low-carbon energy technologies in the future, including but not limited to incentives for energy storage and hydrogen, as well as changes to policies governing the design of electricity markets. Demand changes will require cultural acceptance, increasing familiarity with new technologies and behaviors, and financial incentives to convince consumers to shift away from solutions they have historically used but that might be more carbon intensive than modern alternatives. Some technology changes will encounter agency issues, such as landlord-tenant incentive mismatches that will require policy interventions.

Understanding these constraints is key to identifying approaches that can overcome them.



Decarbonization Topics for Further Consideration

Additional decarbonization topics are worth acknowledging even though they are not directly related to electrification, which is the focus of this report:

1. Some technology, policy, and infrastructure changes can enable energy-saving behavior changes, such as using videoconferencing to reduce the need to fly. Additional considerations include zoning for sustainability, climate resilience, and environmental justice (Velasco and Cohen 2022), as well as expanding public transit, investing in alternative transportation systems such as expanded and connected bike lanes, and improving the walkability of cities (Zagow 2022).
2. Deploying carbon management strategies such as CCUS, direct air capture (DAC), and expanding land sinks as a natural form of carbon sequestration may be needed to reach full decarbonization, as the eight electrification strategies mentioned above significantly reduce emissions but still may not reach all the way to zero emissions. For example, carbon capture can be added to industries that cannot otherwise economically decarbonize and/or be paired with biomass as a net negative carbon technology. In these scenarios, infrastructure to transport and store carbon is needed to meet this new demand, but these technologies have constraints stemming from cost, geology, capture rates, injection rates, site porosity, storage volume, energy availability, technology readiness, and land use. Deployed carbon management strategies are not primary methods of carbon reduction and are not used to extend the life of expensive carbon-intensive processes such as coal generation. Instead, they are used when electrification, energy efficiency, and similar strategies have been cost maximized. IPCC decarbonization scenario analysis has seen a likely reduction in CCS penetration in the power sector between Assessment Report 5 (AR5) and the most recent assessment report (AR6), while carbon management is still expected to be required in the industrial and synthetic fuels sectors.
3. Planning around the transition to net zero will need to consider effects on disadvantaged and marginalized communities to ensure they do not continue to be disproportionately harmed in the process. While the above strategies may achieve net zero, the studies and scenarios evaluated generally lack a complete discussion of who suffers as emissions continue. Capturing carbon from industrial facilities or power plants does not necessarily negate all of the forms of air pollution they produce and thus their effect on nearby communities. For example, studies have shown that people of color are currently exposed to higher levels of fine particulate matter (PM) compared to communities that are predominantly white (Tessum et al. 2019). The current studies also do not fully capture the complex conversation regarding energy poverty and potential tradeoffs with environmental impacts.³

Additional discussion regarding relevant decarbonization topics, including agricultural practices and effects on jobs, is provided in Appendix D.



Future Energy Needs

To understand the potential for expanding electrification in the economy, it is important to first understand the amount and type of energy that may be needed in the coming decades.

Primary and Final Energy

Primary energy is typically described as energy sources that naturally exist and can be harvested (e.g., oil, natural gas, and solar). In the context of this report, final energy will be defined as the forms of energy that are consumed to provide end-use services (e.g., gasoline, hydrogen, and electricity).

Projections of Future Energy Demand

Pathways toward decarbonization result in both a lower primary energy demand and final energy delivered. The reductions in both primary and final energy consumption are achieved through electrification, fuel switching, energy efficiency, modal shifts, and other demand reductions. Despite the reductions in primary demand and final energy delivered, the consumption of electricity is projected to increase. Using electricity for end uses is generally more efficient than using a nonelectric alternative (e.g., a best in class internal combustion engine may be up to 55 percent efficient, whereas a typical electric vehicle motor is 97 percent efficient), thus resulting in more electricity use but lower primary energy use. Delayed electrification slows this impact and yields less reduction in the cumulative sum of energy supply and energy delivered to end uses. Also, in net-zero analyses, less electrification means more energy supply is needed (e.g., increased consumption of gasoline).

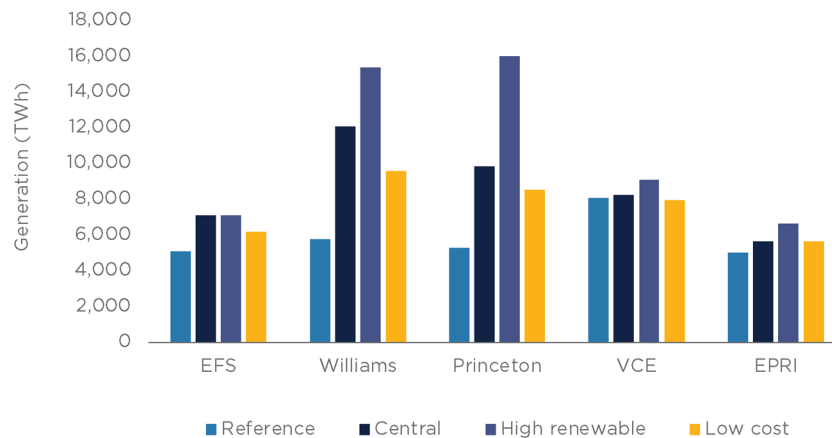
In EFS, the use of natural gas for electricity also lowers primary energy demand due to generation efficiency gains compared with burning coal. Higher renewable energy scenarios result in small increases in primary energy. Bigger increases in primary energy occur when (1) renewables are constrained while the economy attempts to electrify, (2) when power plant retirements are constrained, (3) when transmission is constrained (and thus more curtailment of energy sources occurs), and (4) when less natural gas is available. Typically in international statistics, the input primary energy of wind, solar, or hydro is not measured and only the generated electricity is measured, biasing further the understanding of primary renewable energy versus primary fossil energy demand projections.

Despite similar scenarios modeled, the different studies examined in this report have noticeably different estimates of energy consumption in the coming decades. For example, the studies project that future electricity demand may vary between approximately 5,000 and 8,000 terawatt-hours (TWh) in 2050 in the reference cases (the US consumed almost 4,000 TWh in 2021), as shown in Figure 2. For electrification and high renewables scenarios, the studies show ranges of electricity generation from approximately 5,500 to 16,000 TWh. The wide range in estimated future demand for electricity elucidates the fact that underlying assumptions in the different models have important impacts on how the models estimate future energy needs. Consequently, these assumptions have a critical influence on the required adoption rates of different technologies and solutions to expand electrification and achieve a net-zero future. Thus, it is difficult to provide a simple side-by-side comparison



of the different studies without discussing some of the nuanced results from each of the models. Additional details regarding the demand side considerations are provided in Chapter 3 and Appendix C. It should also be recognized that a comprehensive comparison of each assumption used in each of the studies would be intractable within the context of the goals of this report to summarize the primary findings. The authors refer the reader to each of the studies in question for more detailed discussion of the underlying assumptions.

Figure 2: Generation in 2050 across studies and scenarios



System Costs

Decarbonization strategies such as transmission expansion, renewable energy deployment, carbon management, and electrification retrofits are capital intensive with spending estimates in the trillions of dollars per year by 2050. However, there is wide variation between studies for how expensive reaching a net-zero economy will be; the studies used different metrics and thus were not wholly consistent in their costs reporting.

Princeton estimates that total system costs for a net zero economy reach \$26 to \$28 trillion from 2020 to 2050, an increase of \$4 to \$6 trillion over the reference scenario. Approximately \$9.7 trillion is required cumulatively between 2020 and 2030. Annual cost varies between \$1 and \$2.2 trillion per year and increases as variable generation increases, as shown in Table 3. Similarly, compared to the reference scenario, Williams estimates total energy spending⁴ to range from approximately \$1.2 to \$1.8 trillion per year by 2050, on par with Princeton. In contrast, VCE estimates that achieving net zero in the electric sector will vary between \$2.5



and \$3.2 trillion in total resource costs, which include capital, fixed and variable operations and maintenance, and fuel for electricity, hydrogen, and natural gas. Annual resource costs increase from approximately \$320 billion in 2018 to between \$372 and \$496 billion in 2050 but vary lower and higher year to year depending on the scenario. For example, an increase in transmission installation pushes yearly costs to a maximum of \$525 billion in 2035 in one VCE scenario, while the lowest cost scenario dips to \$246 billion annually in 2030. Similarly, Berkeley calculates that a total investment of \$1.7 trillion in clean energy by 2035 is needed to achieve the 90 percent clean energy goal. Table 3 shows a comparison of costs across the studies, including the EFS's nondecarbonized but electrified future costing \$3.6–\$3.9 trillion total from 2019 to 2050. The cost results from EFS were originally reported in 2016 dollars but have been converted to 2018 dollars here to help facilitate comparison with other studies. It is worth noting that for the majority of cases, the net cost relative to the reference is positive, meaning that a decarbonization pathway will cost more money than the reference scenario. The studies assert that the benefits of taking such action outweigh the cost; this conclusion is in line with IPCC AR6 WGIII as previously noted in the fourth electrification challenge. Additional work is warranted to assess whether the net cost relative to the reference case would remain positive if all system costs and externalities (e.g., nonlinear climate damages to economic productivity, adaptation costs, and health damages) were accounted for beyond the cost descriptions that are summarized in Table 3.

Table 3: Total, annual, and net costs for studies evaluated (2018, dollars)

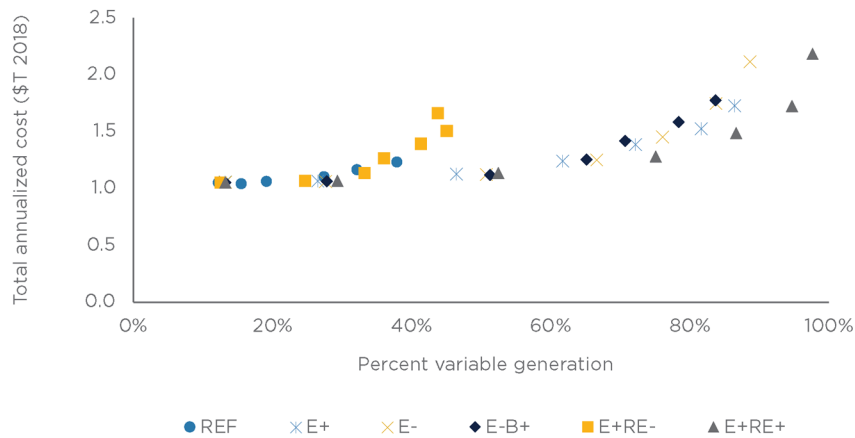
Study	Cost category	Description	Total cost	Annualized cost	Net cost relative to reference
Princeton	Total system costs	Supply and demand side energy system costs, including capital and O&M	\$26–\$28T	\$1–\$2.2T	\$4–\$6T
Williams	Total energy spending	Supply side energy infrastructure, fuels, O&M, incremental cost of demand side equipment		\$1.2–\$1.8T	\$53–\$340B
VCE	Total resource cost	Electricity generation, hydrogen, and natural gas costs	\$2.5–\$3.2T	\$246–\$525B	\$(-11)– \$658B
Berkeley 2035	Clean energy investment	Supply side investment for 90% clean energy	\$1.7T up to 2035		
EFS	Total cost	Transmission, nonfuel O&M, fuel costs, capital costs	\$3.6–\$3.9T		\$491–\$768B

Some of the capital-intensive strategies Princeton includes are the following: \$7 billion investment in public charging infrastructure; \$250 billion for energy efficiency that reduces energy intensity of transportation, industry, and buildings; \$60 billion for new cement plants with carbon capture; \$170–\$230 billion for carbon dioxide (CO₂) pipeline infrastructure; and



\$8 billion for new direct-reduced iron facilities that operate using hydrogen. An estimated \$370 billion in total electricity distribution network investment is needed in the 2020s alone. The Princeton authors also expect that stakeholder engagement will require an additional \$13B investment. Figure 3 shows the range of total cost for each scenario modeled in Princeton as the percentage of variable generation changes.

Figure 3: Total annualized cost compared to percent variable generation in electricity supply, estimated by Princeton



Note: For scenario abbreviations, see Table 2.

Future work could attempt to assess the potential carbon abatement value of each transition step in the models. This could be done using a metric such as levelized cost of carbon abatement. Unfortunately, this type of analysis cannot be completed using the information available in each of the studies in question due to the fact that multiple different investment decisions are made in each of the scenarios within each study. Furthermore, trying to isolate the influence of a single technology or transition step can obscure potential synergies that might only become evident with system-wide optimization models. As such, significant effort would be needed to attribute the value of carbon abatement to a single technology or transition step.

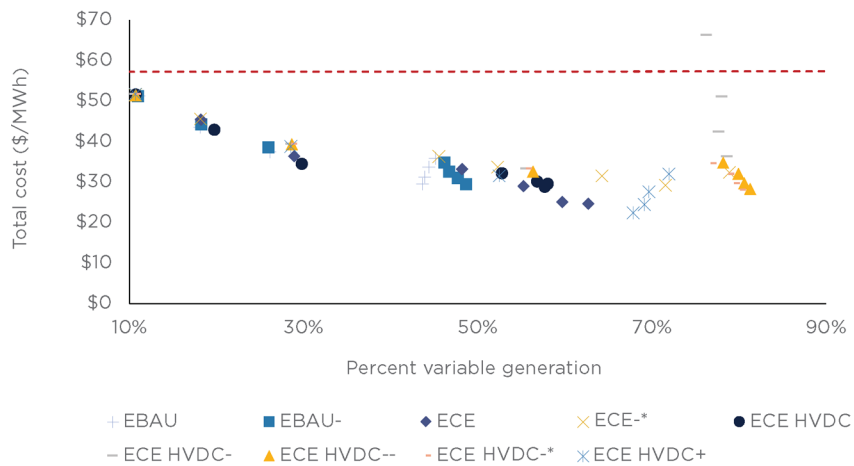
Decarbonization is more expensive for the energy sector overall when no externalities are considered but less expensive per unit of generation. However, when externalities or benefits are considered in the studies, decarbonization is less expensive than the reference scenario. Additionally, the need to install more transmission to accommodate distributed resources and additional renewable capacity (to compensate for variability in generation) increases



total system costs. These capital-intensive strategies lead to an increase in fixed cost driven by increased generation and transmission deployments. However, there is a corresponding decrease in the variable cost of generation due to lower fuel use. Paired, these negatively correlated trends still result in an overall increase in cost, as shown in Figure 3 for Princeton. It is important to recognize that despite the apparent increase in costs, the studies currently under scrutiny did not use a consistent or comprehensive methodology to quantify the impact of all potential externalities associated with maintaining the status quo of a carbon-intensive economy. It has been shown in several studies that the climate and air quality costs associated with the status quo are quite substantial. For example, Driscoll et al. (2021) analyzed the costs and benefits, inclusive of local air quality improvements, for a target of 80 percent carbon-free electricity production by 2030 in the US and found a net present value of \$1.43 trillion in net benefits (benefits less costs), the majority derived from air-quality-improvement-related reduced mortality.

The decline in variable costs of electricity for increased renewable energy deployments can be seen in the data from VCE in Figure 4, where the red dotted line is the initial cost per megawatt-hour (MWh) (i.e., average electricity cost in 2018). Increased flexible demands using off-peak electricity that reduce curtailments further reduce marginal costs.

Figure 4: Total variable and fixed generation cost per MWh compared to percent variable generation in electricity supply, estimated by VCE



Note: For scenario abbreviations, see Table 2.



However, some studies estimate that wholesale energy costs increase with a cleaner electricity system. Berkeley 2035 suggests these costs are about 12 percent higher by 2035 in the 90 percent clean energy scenario relative to the reference case but 10 percent lower than they were in 2020. Similarly, VCE estimates that electricity rates would increase between 9 percent and 41 percent relative to the economic business-as-usual scenario (EBAU) in all but one case (ECE HVDC-), despite being 12 percent to 30 percent lower than rates in 2018. Other studies do not directly quantify electricity rate changes.

Future Energy Infrastructure Needs

Electricity Generation

The electrification of most end uses is a major tenet of a net-zero economy. Deep electrification will increase demands on the electricity sector and thus require increased manufacturing and utilization of hardware to generate and distribute decarbonized electricity.

Decarbonization studies generally share a theme of rapidly eliminating coal, reducing or eliminating natural gas, and increasing renewable generation in the pursuit of expanded electrification. All studies evaluated in this report agree that there will be no deployment of any new coal capacity. However, decarbonization and nondecarbonization studies differ in how quickly coal and natural gas generation are phased out, if they are. Decarbonization studies eliminate coal generation by 2030 or 2035. Nondecarbonization studies see a reduction in coal use in scenarios with high renewable energy use, high natural gas use, emissions constraints, or high electrification, but they do not necessarily see coal generation disappear.

The decarbonization studies do allow for increased natural gas capacity as needed. This capacity is mainly combustion turbines that are used when the models are constrained in a way that it can only deploy renewables. However, most decarbonization scenarios do see natural gas generation decrease to almost zero by 2050. Increases in or continued natural gas use is paired with CCUS or some other carbon offset to achieve net zero.

In contrast, the nondecarbonization studies show an increased use of natural gas in both combined cycle and combustion turbines and continued use to 2050. In NREL's Interconnections Seam Study, there is variation across scenarios via the increased use of natural gas in more efficient combined cycles and a decreased use of combustion turbines. NREL's EFS sees increased electrification leading to more natural gas combined cycle (NGCC) generation. In some decarbonization scenarios, generators utilize hydrogen and natural gas fuel blends, particularly in high renewable energy scenarios. For example, in Princeton, higher blends of 60–100 percent hydrogen or synthetic gas are used, but Williams employs lower (less than 10 percent) blends of hydrogen in all scenarios except for the high renewable energy scenario. Hydrogen is only deployed at large scale when the modeling scenario requires decarbonization of the whole economy.

All electricity studies evaluated show a future heavily reliant on renewable generation (i.e., VRE accounts for 43–91 percent of generated electricity by 2050 in all studies, 47–91 percent in net zero studies), requiring a rapid expansion of clean energy capacity. Decarbonization studies expand these technologies further than nondecarbonization studies. Wind and solar



generation significantly increase across all studies unless specifically constrained by factors such as land use, high renewable energy prices, or low natural gas prices. When land use is constrained, offshore wind generation and residential PV solar generation increase faster. However, concentrated solar power (CSP) does not increase in any study.⁵

Variable generation exceeds firm generation by 2040 in many net-zero scenarios. The studies show no new additions of hydroelectric capacity, and there are generally only minor changes to nuclear capacity, except VCE, which shows significant increases in advanced nuclear technologies in some scenarios. In general, hydroelectric and nuclear generation slightly decrease from current levels to 2050. However, in scenarios where renewables growth is more constrained by cost or land availability, nuclear generation increases; in scenarios where renewables growth is less constrained, nuclear generation decreases. Geothermal and biomass are generally used minimally, except in scenarios that favor expanded biomass, such as Princeton's E-B+ scenario. Energy storage capacity increases later in most studies and corresponds with high renewable or constrained gas scenarios. Table 4 summarizes these comparisons across studies.

Table 4: Changes in US fuel capacity and generation across studies

Fuel	Decarbonization studies	Nondecarbonization studies
Coal	- No capacity additions - Generation eliminated by 2030–2035	- No capacity additions - Generation reduced in scenarios with high renewables, high natural gas, emissions constraints, high electrification
Natural Gas	- Some capacity increase, expansion of NGCT - Generation decrease to nearly zero in most cases - Increases accompanied by CCUS or offset (VCE: natural gas with CCUS noted as clean)	- Some capacity increase, expansion of NGCC and NGCT - Generation eliminated by 2030–2035 (Seams: variation in NGCC, decrease in NGCT generation; EFS: more electrification means more NGCC generation)
Hydrogen	- Used in CCGT capacity and generation blends - More used in full RE scenarios (Princeton: burning high (60–100%) blends of H₂ or synthetic gas; Williams: burning lower, less than 10%, blends of H₂ except in high RE scenario)	Not used
Wind	- Major installations in all studies - Major generation increase, regardless of strategy (electrification, transmission, decarbonization) unless specifically constrained - Mainly onshore wind unless land constrained - Variable generation exceeds firm around 2030 in many net-zero scenarios	

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Fuel	Decarbonization studies	Nondecarbonization studies
Solar	- Major installations in all studies - Major generation increase, regardless of strategy (electrification, transmission, decarbonization) unless specifically constrained - Mainly utility, some residential solar, no CSP	
Nuclear	Generally, limited changes to capacity and generation, unless renewables constrained (in which case nuclear increases) or renewables growth is unlimited (decreases) (VCE: increases are SMR/MSR)	
Hydro	No capacity additions, generation generally unchanged	
Geothermal	Minimally used	
Biomass	Generally minimal (higher under the biomass specific scenario, especially in the Princeton E-B+ [high biomass] scenario)	
Battery	- Increases with high renewables, constrained gas - Used as a firm resource - More use toward 2050	

Note: Wind, solar, nuclear, hydro, biomass, and battery capacity trends are similar in both decarbonization studies and nondecarbonization studies and are therefore appended into a single column. CCGT = combined cycle gas turbine, CSP = concentrated solar power, MSR = molten salt reactor, NGCC = natural gas combined cycle, NGCT = natural gas combustion turbine, SMR = small modular reactor.

While the studies and scenarios are similar early on, they begin to diverge from each other as they approach 2050. In Chapter 2: Supply Side, the authors further compare the generation profiles for the studies' reference scenarios (i.e., BAU cases), the main expanded electrification scenarios, the increased renewable energy scenarios, and the lowest cost scenarios for each of the studies that share the data.

Transmission

Increasing transmission is shown to be a critical strategy in enabling electrification in three ways. First, expanded transmission enables the use of lower cost energy sources that are often located further away from load. Second, it can decrease instances of electricity constraints and curtailments. Third, increased transmission availability reduces the amount of generation capacity needed to reliably meet demand, reducing total system costs. For example, increased interconnection between different regions in the US can help mitigate the variability of wind and solar resources in any given location with the potential to reduce the amount of generation capacity required in all locations. Both decarbonization and nondecarbonization studies agree that there is large value in significantly increasing transmission capacity in the US.

The required scale of transmission expansion is significant. Princeton estimates that \$2.7 trillion in investment will be needed between 2020 and 2050. VCE includes an increase in total resource cost of 70 percent due in part to a 1,200 percent increase in transmission



capacity over that currently installed. These investments are meant to increase connections between the Eastern Interconnection and Western Interconnection, including increased deployment of high-voltage direct current (HVDC) lines across the country. One of the primary goals of the transmission improvements in the decarbonization studies is to enable additional use of renewable electricity generation by accessing natural resources in regions with less land constraints. Additional details regarding transmission in the decarbonization studies is provided in Appendix A: Supply Side Considerations.

Technical Constraints

There are a few important caveats when interpreting and comparing results across the varying studies. When interpreting the results of macro-energy systems (MES) models, the level of operational realism of the power sector implemented in the variety of models can have considerable impact on the outcomes of the electrification and net-zero scenarios. The literature regarding net-zero scenarios suggests that the existing centralized and dispatchable power system will transition to a much more distributed network with levels of system inertia much lower than today (Gaffney et al. 2018; Brinkerink et al. 2022). Traditionally, inertia of rotating machinery has been a critical feature of the power grid to help stabilize the energy supply (e.g., frequency) as demand varies throughout the day. Thus, a variety of modeling innovation issues should be considered by the reader so as to accurately interpret the results of the studies: power grid inertia, ancillary services, and the seasonal and daily variability of renewable energy.

Solar does not provide conventional system inertia to the power grid, although some pilot demonstrations have yielded results showing that VRE supplies could provide some synthetic inertia to help maintain the reliability of the grid (Denholm 2020; Johnson 2019). Wind turbines also only provide very low inertia. In the absence of sufficient inertia, the electricity system can become unstable. To address this concern, a net-zero power system that is deeply electrified should be designed to include new ancillary service requirements for power system reliability, flexibility, inertia provision, and intraday and intraseasonal energy storage within the market design and the policy provision. These are necessary for the technical operation of the grid with higher resource variability and lower system inertia. While rapidly decarbonizing generation capacity, the transmission system and ancillary services of the grid need to be assessed as an enabler to achieve the race to net zero while ensuring a secure and resilient power sector.

The seasonal and daily VRE must also be incorporated into capacity and generation planning to ensure an accurate picture of resource capabilities, including curtailment and impact on firm resource deployment (e.g., nuclear power plants). The models and scenario studies reviewed in this report employ a variety of methods to include weather and the weather's impact on renewable energy resource potential, as well as methods to capture the impact of declining levels of firm power on the grid. For example, if a model allows VRE to have merit order flexibility (i.e., change the priority order of generation technologies entering and exiting the market) but does not model the dampening effects of operational ramp rates of firm power and minimum stable levels on their ability to quickly react to VRE fluctuations due to weather, then the importance of system flexibility, energy storage, and transmission is



underestimated. If the costs of system integration and curtailment are underestimated, the role and costs of firm and flexible dispatchable natural gas and nuclear capacity expansion can thus also be underestimated. As a result, the pace of feasible net-zero electrification may be overestimated.

Market Constraints

In addition to adequately capturing technical constraints, models must be able to capture market constraints. However, the models employed in the net-zero scenario studies do not explicitly consider producer (utilities and independent power producers) and consumer behavior or market structures. This disparity between economic policy simulation and technology optimization modeling used in these studies may lead model outcomes to deviate from reality. For example, electricity provision in the US is broadly divided between regions with competitive wholesale markets with disaggregated electricity generators and load serving entities (LSEs) and regions with vertically integrated electric utilities that both operate generation facilities and directly sell electricity to end users. Profit-maximizing firms and publicly owned cooperatives operating in these different regions face very different market rules and have quite different business models, which in turn affect how they operate existing facilities and their capacity addition and retirement decisions. This inconsistency can lead to very different development patterns even as regulators in these regions push toward common goals of net-zero electricity provision.

Similarly, market structures, from purely competitive wholesale markets to those dominated by very few firms, can also affect the development path for an energy system. For example, Andres-Cerezo and Fabra (2021) show that incentives to operate and invest in energy storage depends on the degree of competition in the wholesale markets, with less competitive markets leading to a less efficient use and investment in storage. Furthermore, actual electricity markets typically operate dispatch behavior based on marginal costs of the generation facilities. This means that the market rate for electricity is not the average cost of generators supplying the grid but rather the marginal cost for the last generator that is dispatched. This dynamic means that a future grid with heavy penetration of near-zero-marginal-cost VRE and large capacities of relatively high-marginal-cost storage systems would likely yield very different seasonal price swings compared to what is currently experienced in most markets (Junge et al. 2022). This type of market granularity adds an additional layer of modeling complexity that the current studies did not thoroughly investigate.

Additionally, MES models do not explicitly account for health impacts, instead approximating them on assumptions associated with policy and technology changes. Princeton estimates approximately 209,000 to 310,000 avoided deaths and \$1.8–\$2.7 trillion in net air quality benefits due to decarbonization, with the lowest savings in the delayed electrification (E-) scenario and the highest savings in the maximized renewable energy scenario (E+RE+). Berkeley 2035 also tracks avoided environmental costs, about 60 percent of which are due to reduced CO₂ emissions and the remainder to reduced exposure to PM2.5. Total estimated cost avoided is \$1.2 trillion in health and environmental damages, including 85,000 premature deaths through 2050, compared to the reference scenario. Avoided deaths are primarily due to reduced exposure to PM2.5 by reductions in sulfur dioxide (SO₂) emissions from coal plants.



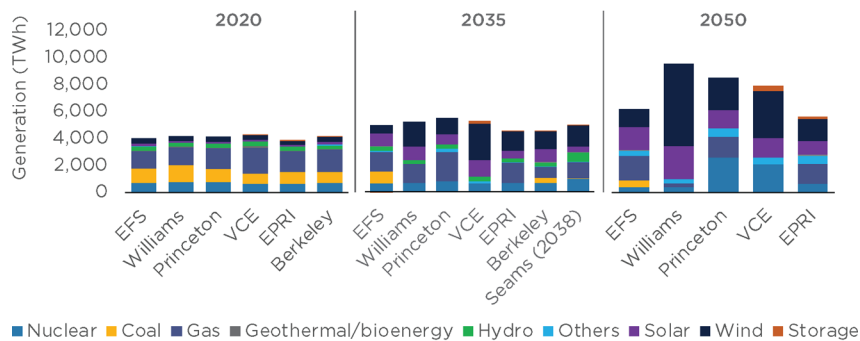
The ability of these MES models to represent outcomes under certain policies is also limited by the types of actors these models represent. Consider, for example, the proposed Clean Electricity Performance Plan (CEPP) under the Build Back Better Act, which sought to give awards or penalties to LSEs based on the amount of low-emitting electricity generation a given LSE procured. The MES models do not explicitly model the behavior of profit-maximizing LSEs and as such did not predict the type of CEPP-gaming actions that others voiced concerns about (Bushnell et al. 2021). These limitations should be kept in mind when one interprets the net-zero pathway operations and costs, as well as policy outcome predictions and benefits of these macro-energy models.



CHAPTER 2: SUPPLY SIDE

The total generation in 2035 for the least cost scenarios, shown in Figure 5, more closely resembles the total generation in the reference scenarios than the electrification and high renewable energy scenarios. The scenarios vary in expectations of generation in 2050. The Williams scenario shows increased generation over all other scenarios despite representing low demand, and EPRI's generation profile for net zero in 2050 is lower than EFS medium electrification scenario generation. Note that Berkeley 2035 and Seams carry their analyses through 2035 and 2038, respectively. Thus, their scenarios are only compared through 2035.

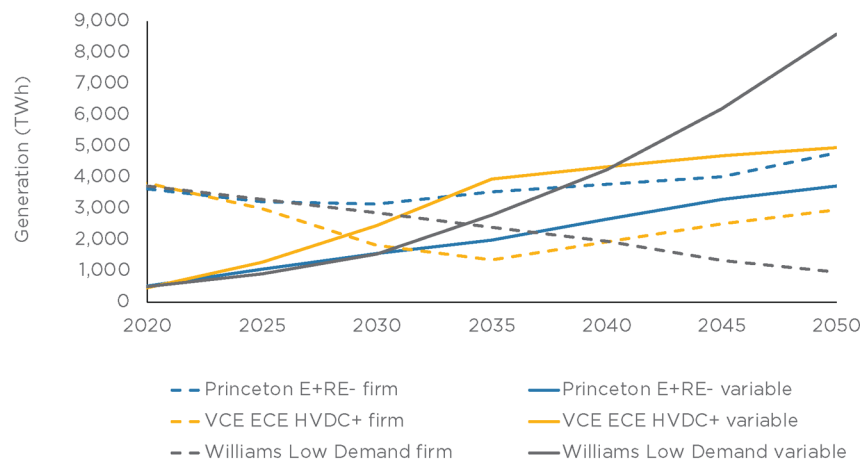
Figure 5: Generation estimated in lower-cost scenarios



Note: This figure is modified from Hausfather and Olson (2021) using the lower-cost scenarios rather than the central scenarios, different years (2035 instead of 2030 and 2040), and additional studies for comparison.

By 2035, coal generation is eliminated or nearly eliminated in all studies except EFS and Berkeley 2035. Natural gas use varies across the studies. Princeton relies on natural gas more than all other studies, and both Williams and Princeton rely on natural gas generation in 2035 more than in the electrification scenario. Williams significantly reduces natural gas use by 2050 as in the electrification scenario. Princeton and EPRI continue to use natural gas to 2050. VCE, on the other hand, nearly eliminates natural gas generation by 2035. Both Princeton and VCE expand nuclear generation after 2035. Variable generation exceeds firm generation prior to 2030 in VCE, prior to 2035 in Williams, and not at all in the other studies (Figure 6).



Figure 6: Firm and variable generation over time in lower-cost scenarios

Note: This figure is modified from Hausfather and Olson (2021) using the lower-cost scenarios rather than the central scenarios and additional studies for comparison. For scenario abbreviations, see Table 2.

The analyses indicate that net zero can be achieved at a lower cost with and without natural gas, as well as with and without increasing nuclear generation. However, all lower cost scenarios still eliminate coal by 2035 and expand renewable energy, though not as rapidly as in other scenarios.

In this analysis, the authors compare supply side electrification scenarios for US-centric net zero studies: Williams, Princeton, VCE, and EPRI. The 2020 starting point for each study varies by scenario but generally begins at 3,900–4,300 TWh of generation, 11–13 percent of which is variable renewable energy produced by wind and solar and 35–41 percent of which is nonfossil produced by nuclear, hydro, geothermal, and bioenergy, as well as wind and solar. By 2050, generation mixes vary across scenarios. Table 5 summarizes the total generation as well as the percent variable renewable and percent nonfossil generation. A deeper discussion of the trends and specific fuels used in each type of scenario as well as additional studies (EFS, Seams, and Berkeley 2035) is included in Appendix B: Comparing Supply Side Scenarios.



Table 5: Comparison of net-zero scenarios in Williams, Princeton, VCE, and EPRI from 2020 to 2050

Scenarios	2020			2050		
	Generation (TWh)	Fraction that is variable renewable	Fraction that is nonfossil	Generation (TWh)	Fraction that is variable renewable	Fraction that is nonfossil
Reference	3,900–4,300	11–12%	35–40%	5,000–8,000	30–62%	50–75%
Electrification	3,900–4,300	11–13%	37–41%	5,600–12,000	47–91%	73–100%
High renewables	3,900–4,300	11–13%	37–41%	6,600–16,000	76–98%	99–100%
Lowest cost	3,900–4,300	11–13%	37–40%	5,600–9,600	44–90%	73–100%

Reference Cases

The reference or business-as-usual scenario for each study is not a net-zero scenario but serves as a reference point for each study for what generation might look like should no policy changes toward electrification and net zero be made. The reference scenarios compared here are Williams, Reference; Princeton, REF; VCE, EBAU; EPRI, Reference; EFS, Reference, Berkeley 2035, Baseline; and Seams, Base Case. The reference scenarios are critical for providing a basis of comparison for all other modeled scenarios. As such, particular emphasis is placed here on first describing the reference scenarios before considering alternatives.

Generation in the reference scenarios reaches 5,000–8,000 TWh in 2050 (which roughly represents a 30–100 percent increase in electricity consumption compared to 2020). Of the total consumption in the reference scenario, 30–62 percent is projected to be variable renewable energy in 2050 and 50–75 percent nonfossil resources. Variable generation exceeds firm generation only in one study. Use of natural gas continues to 2050 in most studies while coal generation decreases but continues to 2050 in two of the net-zero studies and is eliminated in the other two. Increases in renewable generation are delayed closer to 2050 in this scenario compared to others. In contrast, nuclear is projected to decline in most studies by 2050; however, VCE projects a significant increase in nuclear power over the same time frame for the reference case.

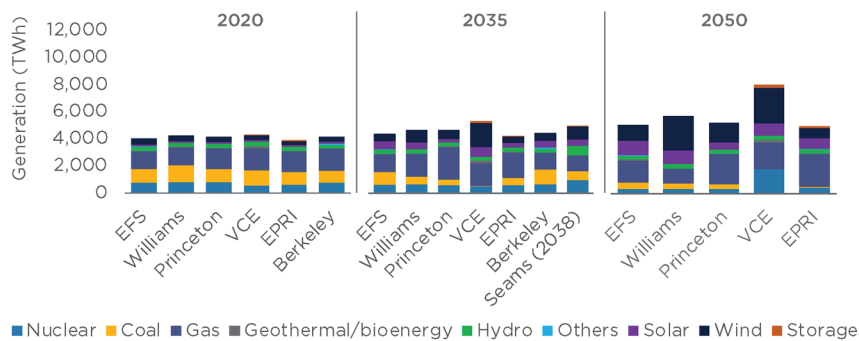
Breakdown of Reference and BAU Scenarios by Study

This section compares each of the studies' reference or business-as-usual scenarios. Depending on the year in which a study began, each of their 2020 total US generation values are around 4,000 TWh, as shown in Figure 7. The studies are generally consistent with each



other at first due to limited feasible rates of change from current base year calibration—the generation consists mainly of natural gas, coal, and nuclear supplemented by renewable resources. VCE starts higher than other scenarios, and EPRI starts lower. In 2035, electricity generation increases slightly from 2020 to an average of 5,001 TWh. Coal generation decreases in most studies and is nearly eliminated in VCE. Berkeley 2035 is the only study to see an increase in coal generation, despite using the same modeling platform as EFS. Natural gas use increases in most scenarios but decreases in Berkeley 2035. Renewables increase in all scenarios with VCE seeing the largest increase by 2035.

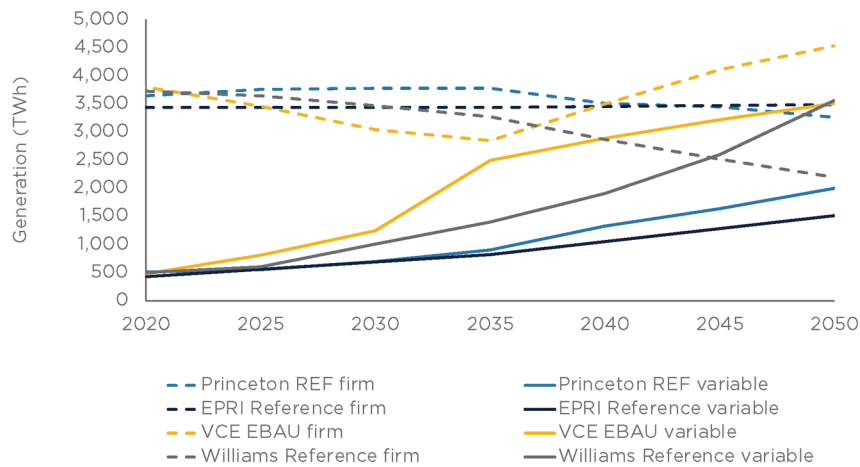
Figure 7: Generation estimated in reference/BAU scenarios



Note: This figure is modified from Hausfather and Olson (2021) using the reference scenarios rather than the central scenarios, different years (2035 instead of 2030 and 2040), and additional studies for comparison.

Through 2050, the trends generally continue. Coal decreases and is eliminated in the EPRI and VCE studies. However, natural gas use diverges and increases in some studies while decreasing in others but is not eliminated in any study. Solar and wind generation expand significantly between 2035 and 2050 in most studies and scenarios. Nuclear decreases in most studies but increases significantly in VCE. Additionally, VCE expects a much higher demand in 2050 in the BAU scenario compared to other studies. In most reference and business-as-usual scenarios, variable generation does not exceed firm generation, except for Williams, where variable generation exceeds firm generation prior to 2045 as natural gas decreases, nuclear decreases, and no firm generation is added to replace those changes, as shown in Figure 8.



Figure 8: Firm and variable generation over time in reference/BAU scenarios

Note: This figure is modified from Hausfather and Olson (2021) using the reference scenarios rather than the central scenarios and additional studies for comparison. For scenario abbreviations, see Table 2.

Electrification

The central electrification scenarios across studies lead to increased generation, mainly renewables, such that by 2050, generation reaches 5,600–12,000 TWh. Renewable generation increases rapidly, and 47–91 percent of 2050 generation is variable renewable generation. Nonfossil generation reaches 73–100 percent. Variable generation exceeds firm generation in three of the four net-zero studies. (The central electrification scenarios compared in this report are EFS, High; Williams, Central case; Princeton, E+; VCE, ECE; and EPRI, Net zero by 2050.)

High Renewables

The high renewable scenarios extend this trend further with high electrification and increased use of renewable energy. By 2050, the renewable scenarios reach 6,600–16,000 TWh of generation, 76–98 percent of which is variable renewable electricity and 99–100 percent of which is nonfossil. With a rapid transition to renewable energy, variable generation exceeds firm generation by 2030 in all scenarios. It is important to note this high variable renewable penetration is reached while also considering grid reliability constraints. Small decreases in firm generation are matched with much larger increases in renewable generation. (The high renewables scenarios compared here are Williams, 100% renewable primary energy; Princeton, E+RE+; VCE, ECE HVDC-; and EPRI, 100% renewable by 2050.)



Lowest Cost

In contrast to the previous scenarios, there is large variation in how to achieve low-cost electrification on a path to net zero, including with or without natural gas or nuclear energy. Solar and wind increase but not as rapidly as the high electrification or high renewables scenarios. The lower rate of increase in renewables is due to the additional near-term costs of expanding transmission and expanding capacity to meet reliability needs. For the most part, the studies investigated herein support the claim that meeting the energy demands of the coldest and hottest days of the year with 100 percent VRE appears to be more expensive than a diversified portfolio. In Williams, the lowest cost scenario is the lowest demand scenario. Lowest cost scenario generation reaches 5,600–9,600 TWh, made up of 44–90 percent variable renewable generation and 73–100 percent nonfossil resources. Variable generation exceeds firm in two of the four studies, suggesting that high levels of VRE penetration will play a critical role in achieving the lowest cost outcomes on the path to net zero. It is worth noting that coal is eliminated from the energy mix by 2035 in nearly all of the low-cost scenarios. (The low-cost scenarios compared here are Williams, Low demand; Princeton, E+RE-; and VCE, ECE HVDC+.)

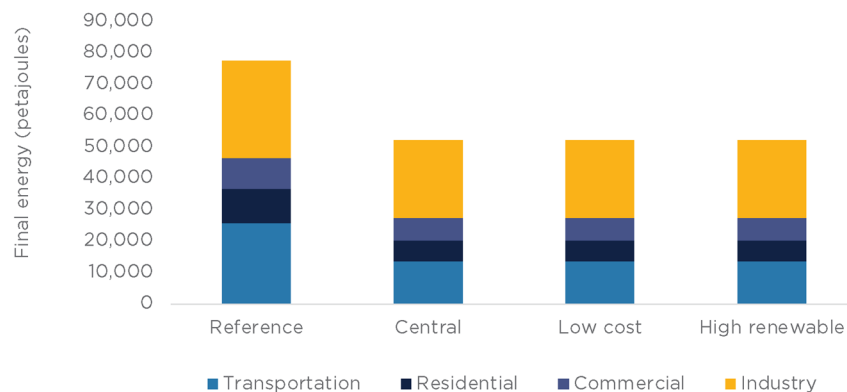


CHAPTER 3: DEMAND SIDE

The following conclusions regarding changes to electricity demand are all drawn from surveying the aforementioned studies that also included strategies to electrify the economy: Princeton, Williams, and EFS. Adjusting energy demand through increased electrification and energy efficiency is key to decarbonization. The considered studies mainly expand electrification across the residential, commercial, and transportation sectors, while the industrial sector was assumed harder to electrify. Flexible demands that allow for demand shifting throughout the day or demand response to reduce demand during periods of peak load play a key role in ensuring reliability of a highly electrified economy paired with a decarbonized grid.

The transition to more efficient technologies also reduces the total final energy needed. While energy efficiency and conservation alone cannot achieve net zero, they should be paired with electrification and other decarbonization strategies to minimize the need for additional infrastructure while also keeping the system as affordable as possible. Similarly, while electrification alone has efficiency benefits, it will not achieve net zero by itself; it must be paired with a net-zero electricity sector (e.g., electric vehicles can improve fuel efficiency, but to achieve net zero the vehicles must receive their electricity from zero-carbon sources). Projections of energy demand by sector in 2050, based on different scenarios in the Princeton study, are provided in Figure 9. Additional detailed discussion regarding demand side dynamics for electrification is provided in Appendix C.

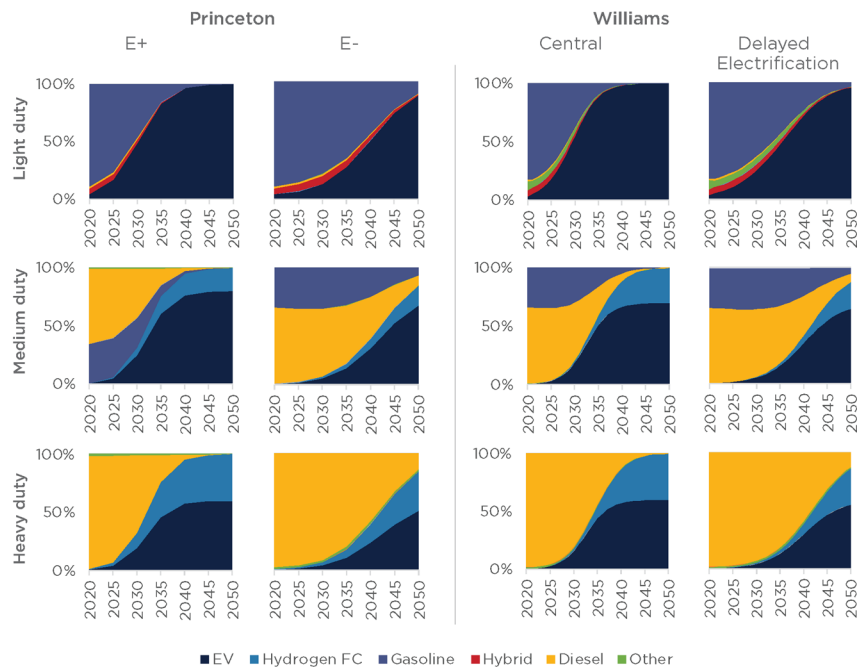
Figure 9: Final energy demand by sector in 2050, estimated by Princeton



Transportation Demand

The studies show that decarbonizing transportation involves relying heavily on EVs across all vehicle types, as well as utilizing some hydrogen vehicles. However, a minority of vehicles still consume diesel or gasoline by 2050, as shown in Figure 10.

Figure 10: Transportation sales in Princeton and Williams



Note: The E+ and Central scenarios are the high electrification scenarios for Princeton and Williams. The E- and Delayed Electrification scenarios both delay the adoption of electrification technologies. "Diesel" includes Reference TDI Light-Duty, Reference Diesel Heavy-Duty Vehicle, and Reference Medium-Duty Diesel Vehicle; "EV" includes Electric Light-Duty - 200 mile range, Electric Light-Duty - Long Range, Electric Heavy Duty Vehicle, and Battery Electric Medium-Duty Vehicle; "Gasoline" includes Reference Gasoline Light-Duty, Reference Gasoline Heavy-Duty Vehicle, and Reference Medium-Duty Gasoline Vehicle; Hybrid includes Diesel - Electric Hybrid Light-Duty, Electric - Gasoline Hybrid Light-Duty, PHEV - 25 mile range - Light Duty, PHEV - 50 mile range - Light Duty, Diesel Hybrid Heavy-Duty Vehicle, Hybrid Diesel Medium-Duty Vehicle, and Hybrid Gasoline Medium-Duty Vehicle; "Hydrogen FC" includes Hydrogen Fuel-Cell Light-Duty, Hydrogen FCV Heavy-Duty Vehicle, and Hydrogen Fuel Cell Medium-Duty Vehicle; and "Other" includes CNG Light-Duty, Propane ICE Light-Duty, Reference Flex Fuel Light-Duty, LNG Heavy-Duty Vehicle, Reference Propane Heavy-Duty Vehicle, Reference LPG Medium-Duty Vehicle, and Reference Medium-Duty CNG Vehicle.



Aggressive electrification of transportation requires a rapid expansion of electric vehicle sales across all vehicle types in the 2020s, as well as the need to expand charging infrastructure and electrify mass transit. In high electrification scenarios, battery EVs reach 100 percent of light-duty vehicle sales, and a combination of hydrogen and battery EVs reach 100 percent of medium- and heavy-duty trucks between 2040 and 2050. With increased sales, these vehicles reach 90–97 percent of total stock in highly electrified scenarios. In delayed electrification scenarios, these vehicles reach 85–90 percent of sales by 2050. While the majority of the envisioned EV sales are expected to be battery powered vehicles, some manufacturers continue to place focus on hydrogen fuel cell solutions. Additional breakthrough in fuel cell or hydrogen storage technology and/or greater adoption of hydrogen in other parts of the economy might lead to additional adoption of hydrogen, particularly for applications with rapid refueling needs.

Residential and Commercial Demand

Electrifying residential and commercial buildings is an important component for decarbonization in the studies. Ensuring technologies shift to the most efficient alternatives available helps reduce the timing and magnitude of peak demand, which reduces the total system costs. Electrifying residential and commercial demand includes relying mainly on electric appliances for cooking and heat pumps for climate control and water heating. Aggressive electrification requires rapid expansion in heat pump sales for space and water heating to over 50 percent of the market share in the 2020s in Williams and 100 percent of sales between 2030 and 2040 in both Princeton and Williams, leading to 95–100 percent of total stock by 2050. In delayed electrification scenarios, sales only approach 95–100 percent by 2050. Electric residential cooking follows a similar trajectory. However, in the commercial sector, some gas use continues through 2050 for cooking.

Ensuring the public is aware of the broader health and environmental damages of current energy infrastructure could encourage progress in electrifying residential and commercial buildings. An increasing body of evidence shows the health risk of indoor pollution from use of natural gas for cooking in buildings (Nicole 2014, Lee 2002, Hollowell 1980, Zhao 2021, Volkmer 1995) and of local outdoor air pollution from burning fossil fuels (Perera 2017, Kotcher et al. 2019, Perera et al. 2019, Kampa & Castanas 2008). Awareness of this topic could help accelerate the adoption of electric cooking solutions in the residential sector, for example.

Industrial Demand

The industrial sector is the slowest to electrify in the studies, but changes from other sectors ripple through. For example, the electrification of transportation reduces the demand for petroleum products, a major output of the industrial sector. Princeton estimates final energy demand for industry can be reduced by 5–6 exajoules (EJ) (1,400–2,000 TWh), a decrease of 17–20 percent from the Reference to the E+ and E- scenarios in 2050. While some industrial processes, such as iron and steel making can electrify, other hard-to-electrify industrial demands include processes that require high temperature heat (e.g., conventionally met by burning natural gas) and chemical feedstocks. To decarbonize these demands, the studies model that the industrial sector will transition to synthetic fuels (e.g., fuels derived from low-carbon hydrogen), deploy carbon capture, or both when electrification is not an option due to technical or economic constraints.



CHAPTER 4: RECOMMENDATIONS

Electrification

The pathway to net zero requires multiple economy-wide shifts to happen simultaneously, including a broad expansion of electricity production and consumption. The following recommendations include those made by the studies that dig into the transformative changes and their effects on the economy.⁶

Key recommendations across studies include (1) decarbonizing electricity, (2) electrifying end uses, (3) lowering energy demand including by reducing waste, and (4) increasing transmission, distribution, and energy storage infrastructure.

All the studies made clear that the electric sector needs to decarbonize. Coal requires retirement by the early 2030s, and wind and solar capacity must rapidly deploy early to become the largest source of electricity by about 2035. Decarbonizing electricity is a key component to decarbonizing other sectors of the economy. More transmission and distribution are needed to support lower costs as renewable energy expands and electricity loads grow. Increasing energy storage capacity adds firm supply that can be flexibly powered by renewable electricity at off-peak times and deployed during times of peak power demand—though it is not deployed in all study scenarios. In addition, some studies highlighted the opportunity to leverage the expansion of VRE to power useful energy services during off-peak periods, including the production of hydrogen.

When considering the logistical challenges to expand electrification, it is useful to consider the number of actors involved with each decision on the supply side and demand side. For example, there is less broad representation and involvement from the public with building, financing, and regulating utility scale electricity production. On the other hand, deployment of heat pumps, electric vehicles, and electric stoves ultimately requires uptake by individual consumers (i.e., millions of decision makers) and prosumers who have different decision criteria associated with cultural acceptance, familiarity, and financial costs. Deployment will also require an associated growing workforce to install and maintain the products. As a result, there may be an easier logistical path toward achieving the first key recommendation of decarbonizing electricity generation compared to achieving the second key recommendation of electrifying end uses.

Identifying how to effectively engage individuals is a critical step to achieving this second key recommendation of electrifying end uses (Revez et al. 2022, Mullaly et al. 2022). Consumer and installer incentives may be needed to increase uptake and ensure people at all income levels are able to afford the energy efficient technologies and retrofits needed to adjust from gas to electric heating, for example. These solutions and policies will need to be deployed at economy scale during the 2020s to meet most of the timelines described in the studies examined in this report.



Some of the studies also discussed opportunities to enable electrification and reduce the carbon intensity of cities through strategies intended to reduce energy demand, including investing in mass transit and increasing the ability for residents to walk or bike to their destination. While these solutions seem logical to meet the third key recommendation to lower energy demand, the MES models reviewed do not explicitly include metrics such as walkability in their analytical framework, instead modeling general assumptions of energy conservation. As a result, one must rely on other literature to substantiate the claims about the importance of improving the design of cities to expand electrification, reduce energy consumption, and minimize carbon emissions (Gaur et al. 2022, Grubler et al. 2018).

Expanded production and demand of electricity will also require expansion of the transmission and distribution network. Some of the studies estimated that over \$1 trillion will be needed to deploy sufficient transmission infrastructure to achieve the required levels of electrification on a pathway to net zero. The expanded transmission system would enable greater use of solar and wind assets located in regions with good natural resources. Furthermore, a strengthened transmission and distribution system would reduce the amount of curtailment and congestion while also increasing the resilience of the energy infrastructure in the United States (Busby et al. 2021). Despite the apparent benefits of an improved transmission system, it is unclear whether the studies fully capture the project risks associated with transmission expansion, including environmental, legal, and financial challenges that can manifest with large scale infrastructure projects.

While many of the electrification strategies and technologies are readily available to be deployed, more innovations and research will be needed to develop new technologies at scale and reach the deployment pace required within the scenarios. Many of the studies, including VCE and Princeton, emphasize the importance of continuing to invest in maturing technologies, especially clean firm generation like advanced nuclear reactors (e.g., SMR and MSR) and advanced geothermal, in addition to carbon capture for power and industry, hydrogen production and combustion, inexpensive long-duration storage, synthesis of fuels, novel electricity-centric manufacturing methods for steel, high-yield bioenergy, and direct air capture. Active stakeholder involvement in electricity market design will also be required to adopt and integrate novel technologies as quickly as possible. A future grid that is heavily reliant upon VRE, energy storage, and other novel systems may require unique approaches to ensure that the market incentivizes sufficient assets to deliver the affordable and reliable electric grid that communities will expect.

Beyond Electrification

Electrification has significant potential to help decarbonize the economy. However, electrification alone is insufficient to achieve a net-zero future. More research is needed for the currently hard-to-eliminate emissions in aviation, long-distance transport, shipping, petrochemicals, and structural materials, as well as improved methods for reliable, cost-effective systems integration (Elsevier Analytical Services 2021). To address these applications that are hard to electrify due to technical or economic constraints, the net-zero studies recommend scaling up carbon management strategies through CCUS, DAC, and enhancing land sinks. A carbon transportation network would be required to move captured carbon for



either useful purposes or permanent sequestration. Reducing demand for products such as raw steel can also help reduce the need for carbon capture. Additional discussion regarding decarbonization issues beyond electrification, including carbon management strategies, is provided in Appendix D.

Enhanced land sinks (e.g., forests and agricultural soils) are very likely needed to further offset carbon emissions.⁷ Additionally, non-CO₂ emissions, particularly those that cannot be abated through electrification, must also be managed in order to reach net zero greenhouse gas (GHG). This recommendation includes refrigerant (a potent greenhouse gas) management and use of alternatives with low global warming potential. It also includes reducing methane (CH₄) leaks and flares, for example, in current upstream oil and gas operations, at wastewater facilities, at landfills, and in industry.

Science, technology, engineering, and mathematical research needs to be better integrated with other fields such as social sciences, humanities, and policy to understand the broader implications of infrastructure design (Elsevier Analytical Services 2021). Employment opportunities will change as these sectors transform. Workers must be trained for the jobs required, and attention will need to be paid to communities that will experience high job losses.

Finally, transformative changes require public consent for land use changes, for uptake of electrifying technologies, and for any policy shifts required to reach net zero, such as redirecting fossil fuel subsidies to low-carbon technologies or streamlining clean infrastructure permitting. As discussed in Chapter 3, ensuring the public is aware of the broader health and environmental damages of current energy infrastructure could encourage progress in this area. Greater awareness of the health and environmental damages of existing energy infrastructure could help accelerate the adoption of electric cooking solutions, for example. Additionally, increasing the public's awareness of life cycle emissions impacts of different products (e.g., variations in manufacturing practices that result in greater emissions) will be critical to educating a population to achieve a net-zero system.

The studies discussed in this report show that there are paths to achieve net-zero carbon emissions. However, to reach this goal, significant, transformative change will be needed in every sector of the economy.



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APPENDIX A: SUPPLY SIDE CONSIDERATIONS

A.1 Transmission

Increased transmission is needed to match increasing generation, ensuring new resources can reach increased demands due to electrification. Seams, which focused on the grid and cost impacts of transmission, found that it will be cost effective to increase connections between the Eastern Interconnection and Western Interconnection in the US. A macrogrid of new generation HVDC lines connecting the nation, including running through Texas, is also an option but was found to not be the most cost-effective strategy evaluated. Instead, expanded, optimized B2B and HVDC connections between the Eastern Interconnection and Western Interconnection would be the most cost-effective strategy for the country through the end of the study (2038). The Seams analysis did not consider the impacts of higher electricity demand via expanded electrification or the increased renewable energy sources considered in the other decarbonization studies.

The studies show larger increases of transmission are needed to accommodate increases in renewables. However, both renewables and transmission are constrained by land availability. To account for future electrification and changes in electric supply, the decarbonization studies estimate large increases in HVDC connections across the country. Princeton estimates in the E+ scenario that a 60 percent increase in transmission is needed by 2030, and transmission will need to more than triple by 2050 to further connect more wind and solar energy to the grid. VCE models five HVDC macrogrid scenarios. The HVDC scenarios estimate an increase of 4.9 to 12.1 times the MW of installed transmission in use in 2018 by 2050, compared with a 60–70 percent increase for the BAU and aggressive electrification (ECE) scenarios. Berkeley 2035 also estimates that a large investment is needed for transmission, particularly within the Eastern Interconnection. While not a decarbonization study, Electrification Futures Study also estimates that more long-distance transmission will be needed with higher electrification, particularly in scenarios with less natural gas and more renewables.

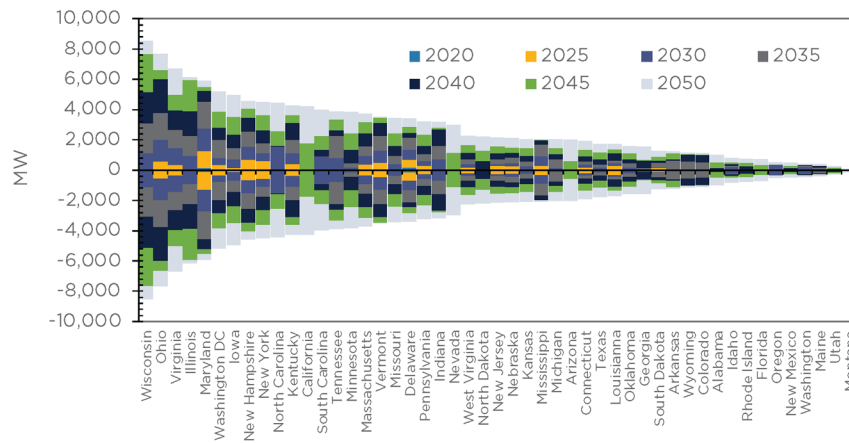
While increasing transmission is necessary to enable decarbonization, it is not sufficient to achieve net-zero alone. Increasing transmission must occur alongside other strategies such as electrification of end uses and decarbonization of electricity generation to be fully effective.

While studies agree large amounts of transmission are needed, the results disagree on location.⁸ In three studies, the largest increases are in the Mid-Atlantic/Great Lakes and Texas. Berkeley 2035 expects transmission increases in Texas and large increases in the Eastern Interconnect. Williams estimates more transmission will be out of Louisiana and the Ozarks and the Mid-Atlantic/Great Lakes to other parts of the country with very little to or from Texas. VCE (ECE scenario) also estimates large transmission increases are needed for import and export in Mid-Atlantic and Great Lakes states. Princeton (E+ scenario) expects the largest increases in transmission needs in Texas, California, New Jersey, and New York. Figure 11 shows the transmission increases estimated in the VCE ECE scenario and Princeton E+ scenario. The top 10 states from each list are highlighted in the other one, e.g., because Texas is in the top 10 for Princeton (right side of Figure 11), it is highlighted in VCE's results (left side of Figure 11)

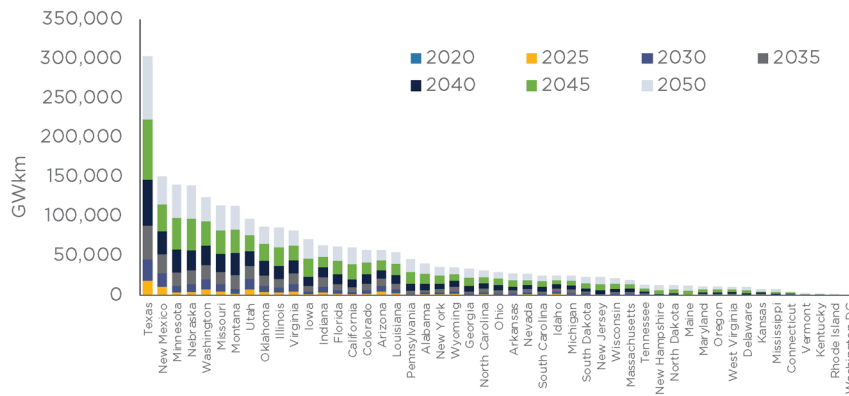


Figure 11: Comparison of transmission increases by state in VCE (ECE scenario) and Princeton (E+ scenario) transmission capacity

a. Added transmission capacity, exports and imports



b. Added HV transmission capacity for wind and solar



Note: Figure 11a compares additional transmission capacity to transmission capacity in 2018. Figure 11b compares additional wind and solar base spur intra-state transmission capacity to transmission capacity in 2020.



A.2 Energy System Reliability

Reliability is an important component of a viable electricity system. Electricity supply and demand must always be matched. Thus, increased demand that is met with increasing shares of variable energy supply presents challenges for grid operators. One way to enable a larger penetration of VRE sources while ensuring the reliability of the grid is to make the demand side more flexible in how it operates. This concept is often described as demand response, which describes a strategy in which a consumer of electricity can ramp up or down based on the needs of the grid. To maintain reliability, the considered studies rely heavily on more flexible loads such as direct air capture (DAC), electrolysis, and electric boilers that can respond to the variability of wind and solar. It is assumed that some portion of the load is able to strategically shift electricity use to balance variation in available renewable energy supply. For example, in Williams 100 percent RE and Princeton E+RE+ (increased renewable energy) scenarios, there is higher electricity demand for hydrogen electrolysis, but that demand is expected to be able to ramp up and down to not only produce the needed hydrogen to help decarbonize the economy but to also help mitigate the impacts of a changing electricity supply.

All study scenarios include generation resources that are less variable in nature compared with wind and solar. These energy assets are described as firm generation, including nuclear, natural gas with carbon capture, and/or natural gas plants burning high hydrogen blends. Some scenarios also increase battery storage or deploy advanced nuclear technologies. In the event that a given scenario has higher deployment rates of less firm generation sources, the studies generally compensate for intermittency by installing higher capacities of variable resources and associated high-voltage transmission.

Additionally, the models used by Princeton and Williams (RIO and EnergyPATHWAYS) and VCE's WIS:dom model account for reliability in scheduling power dispatch throughout the year. Williams notes that fuel and energy storage are tracked in the reliability analysis built into RIO. ReEDS, the capacity planning model used by Electrification Futures Study and Berkeley 2035, includes grid services meant to support reliable grid operations but does not reflect all aspects of grid reliability. Neither EFS nor Berkeley 2035 includes a full reliability assessment. However, the Berkeley 2035 authors did conduct scenario and sensitivity analyses to ensure that demand is met in all periods.

Grid reliability is also affected by weather and climate (Yalew et al. 2020). For example, freezing temperatures can inhibit generation at power plants as it did throughout the southern US in February 2021, and water supply constraints can limit hydroelectric and thermoelectric power supplies (Glazer et al. 2021, Busby et al. 2021). WIS:dom and ReEDS both include weather or climate constraints in modeling capacity available for generation.

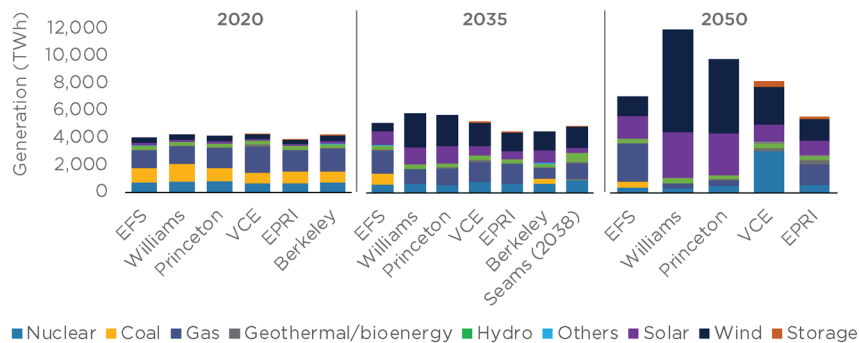


APPENDIX B: COMPARING SUPPLY SIDE SCENARIOS

B.1 Central Electrification Scenarios

The central electrification scenarios compared in this report include the following: Electrification Futures Study, High electrification; Williams, Central; Princeton, E+; VCE, ECE; and EPRI, Net zero by 2050. Berkeley 2035 only has one scenario aside from the reference. That scenario is compared for 2035 in this section as well as the next two sections. The Seams scenario for increased HVDC and B2B connections (D2b), coupled with high variable generation, is compared here as well as in the next two sections. A comparison of generation in the electrification scenarios for the studies is shown in Figure 12.

Figure 12: Generation estimated in electrification scenarios



Note: This figure is modified from Hausfather and Olson (2021) using different years (2035 instead of 2030 and 2040) and additional studies for comparison.

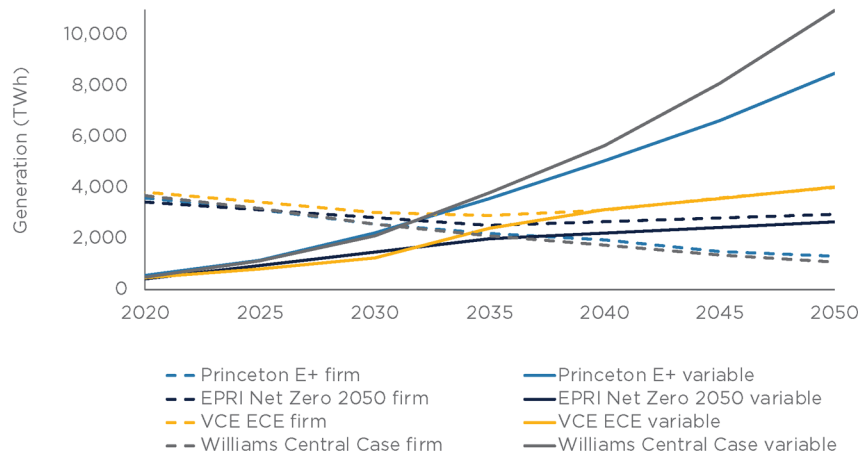
Total generation in 2035 for the electrification scenarios (which are also net-zero scenarios, except for EFS and Seams) varies across studies more so than in the reference scenarios. Coal generation is eliminated or nearly eliminated in all net-zero studies, as well as in the Seams scenario by 2035. Coal is still used in Berkeley 2035 and Electrification Futures Study. Similarly, natural gas use decreases by 2035 and is eliminated or significantly reduced by 2050 in most net-zero studies but increases in Electrification Futures Study and EPRI's analysis. It is evident that the studies agree that when the goal is net zero, coal generation must be eliminated, and natural gas generation must decrease. However, when the goal is simply expanding clean energy as in Berkeley 2035, or electrification as in Electrification



Futures Study, coal is not necessarily eliminated, and natural gas use generally expands.

All studies show a large increase in wind and solar generation, and some also show expanded geothermal, bioenergy, and energy storage. Additionally, VCE shows significant expansion of nuclear generation. Deploying more renewable energy generation coincides with an increase in total generation in 2035 and much more so in 2050, as shown in Williams and Princeton. Decreases in firm coal and natural gas generation that is not replaced by nuclear or energy storage coincide with very large increases in renewable energy. Rather than significantly curtail renewable energy during periods of low demand, some studies employ increased levels of flexible loads, which also, in turn, increase total generation demands. In Williams and Princeton, variable generation exceeds firm generation in the early 2030s, and VCE does so by 2040, as shown in Figure 13. Variable generation does not exceed firm generation in Electrification Futures Study's or EPRI's analyses.

Figure 13: Firm and variable generation over time in electrification scenarios



Note: This figure is modified from Hausfather and Olson (2021) using additional studies for comparison. For scenario abbreviations, see Table 2.

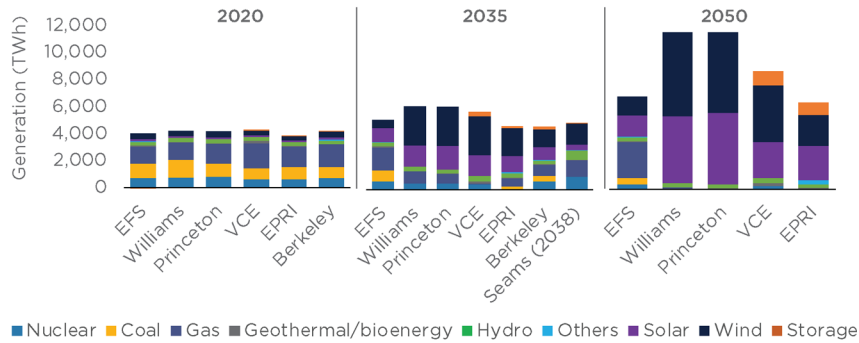
B.2 High Renewables Scenarios

The high renewables scenarios compared here are Williams, 100 percent renewable energy; Princeton, E+RE+; VCE, ECE HVDC-; and EPRI, 100 percent renewable by 2050). The EFS does not have a high renewable scenario; instead, the High electrification case is shown here



for reference. The Berkeley 2035 standard scenario and the Seams D2b VG are used in this comparison as in the previous one. The studies are compared in Figure 14.

Figure 14: Generation estimated in high renewable energy scenarios



Note: This figure is modified from Hausfather and Olson (2021) using the high renewable scenarios rather than the central scenarios, different years (2035 instead of 2030 and 2040), and additional studies for comparison.

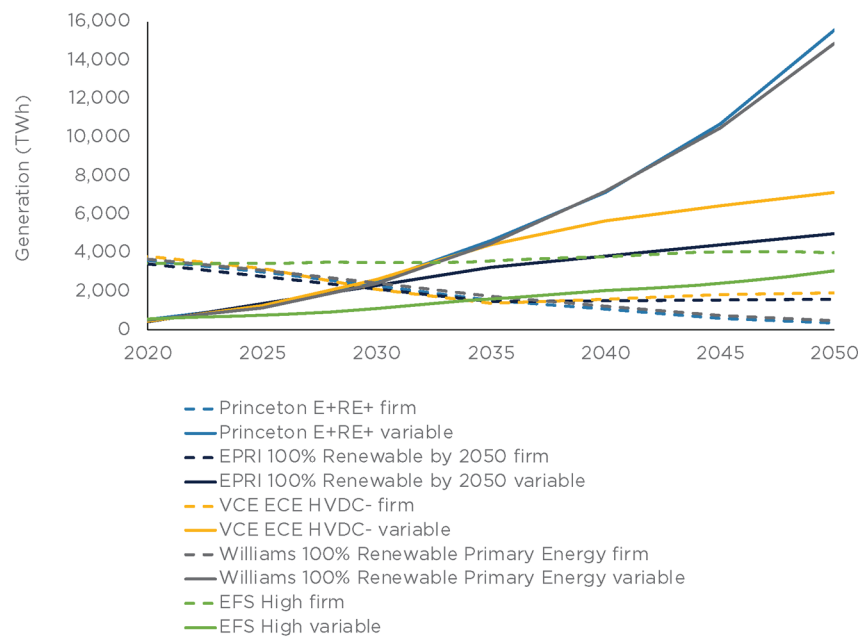
Total generation in 2035 again varies across studies as in the electrification scenarios. Coal generation is eliminated or nearly eliminated by 2035 in most net-zero studies. However, unlike in the electrification scenarios, coal is still used in the EPRI study. All studies decrease nuclear generation, and three of the four net-zero studies eliminate nuclear completely by 2050, as they have a 100 percent renewable energy goal. However, EPRI eliminates nuclear by 2035 and, in doing so, compensates by extending the life of coal generation beyond what occurs in the net-zero scenario. Also, as in the electrification scenarios, natural gas use decreases by 2035 and is eliminated or significantly reduced by 2050 in all net-zero studies. However, the reduction of natural gas generation in the high renewable energy scenarios is deeper than in the electrification scenarios in the previous section. When net-zero goals are accompanied by renewable energy expansion targets, reduction of coal and natural gas generation generally occurs more rapidly.

All studies show increased expansion of wind and solar generation in their high renewables scenarios over the electrification scenarios, with variable generation exceeding firm generation prior to 2030 in them all. Some studies also show expanded use of geothermal and bioenergy feedstocks for electricity generation. Geothermal presents one of the more unique sources of renewable power due to its firm, dispatchable nature. Additional advancements in geothermal technology could help lower its projected cost and allow it to be installed within a time frame to make it a larger contributor to the decarbonization effort prior to



2050. Energy storage is a bigger strategy in 2050 for VCE's and EPRI's analyses than it is in the electrification scenarios; both studies use energy storage to replace larger losses of firm generation. Decreases in firm generation are again matched with large increases in renewable generation as in the electrification scenarios. Deploying more renewable energy generation again coincides with an increase in total generation in 2035 and much more so in 2050, as shown in Williams and Princeton (see Figure 15). It is worth noting that none of the high renewable scenarios that implement least cost optimization achieve 100 percent renewable adoption across the electricity generation infrastructure.

Figure 15: Firm and variable generation over time in high renewable energy scenarios



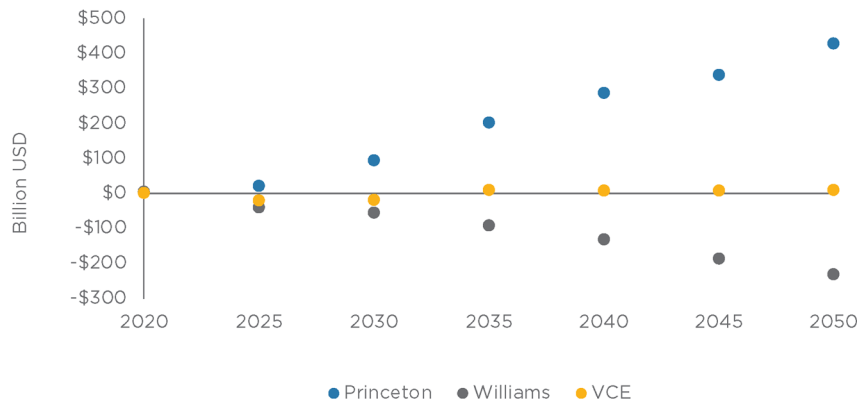
Note: This figure is modified from Hausfather and Olson (2021) using the high renewable energy scenarios rather than the central scenarios and additional studies for comparison. For scenario abbreviations, see Table 2.



B.3 Lower Cost Scenarios

There is large variation across studies in how to achieve net zero, particularly at least cost. As cost minimization models, each study minimizes cost within the constraints of the scenario. Thus, the studies evaluated here are the lower cost options among the set of scenarios in each study, given the assumed constraints on the model but not necessarily the lowest possible cost, in the absence of scenario specific constraints. The choices and assumptions authors made to build each scenario influence which scenario ends up with a lower cost within each study. Figure 16 shows one result of the variations in priorities and assumptions via a difference in annual cost between the lower cost scenario and the reference or BAU scenarios for Williams, Princeton, and VCE. The low-cost scenarios compared in this figure are Williams, Low demand; Princeton, E+RE-; and VCE, ECE HVDC+. It is critical to recognize that each of the studies are reporting costs in different ways; it is challenging, therefore, to draw conclusions between the studies if one only looks at reported costs. This potential source of confusion is being purposefully highlighted here, so the reader understands the complexity of comparing the reported costs in the different studies. In this section, the authors also include Electrification Futures Study, Medium electrification; and EPRI, Net zero by 2050. The Berkeley 2035 Baseline scenario and the Seams D2b VG are used in this comparison as in the previous two.

Figure 16: Difference in reported total annual cost between lower-cost scenario and reference/BAU



Note: This figure compares total annualized system costs in Princeton, total annual energy costs in Williams, and total annual resource costs in VCE. It should be recognized that there are differences in how each study reports costs, which leads to the wide discrepancy in the reported results in the figure.



While it is impossible to know the optimal path to achieve a net-zero economy, the pathway will almost certainly be influenced by relative cost. As such, one might be able to conclude that the lower cost scenarios from each of the studies might also be likely resilient paths to achieve the goal of eliminating emissions from the economy, depending on the assumptions inherent in the scenario, such as behavioral changes leading to energy conservation.



APPENDIX C: DEMAND SIDE CONSIDERATIONS

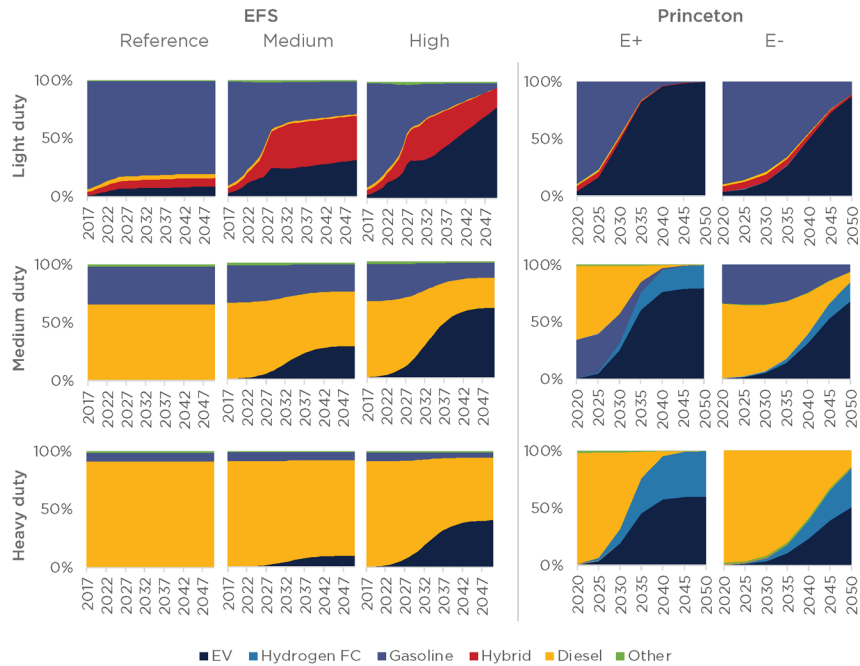
Three of the studies evaluated—Princeton, Williams, and EFS—discuss demand side strategies to reach net zero. Princeton and Williams both show technology trajectories and exhibit similar timing and magnitude of transitions across technologies and sectors. Princeton also notes that equipment replacements are assumed to occur at end of life to avoid stranded asset costs and reduce total replacements costs.

EFS also shows pathways to electrification across Reference, Medium, and High electrification scenarios, where the Reference scenario maintains existing policies, the Medium scenario is loosely consistent with favorable economic conditions, and the High scenario is more transformational. The greater efficiency of electric technologies in the High scenario yields reductions in final energy consumption up to 21 percent, relative to the Reference. However, these transitions are notably slower than in the decarbonization studies. NREL's high electrification scenario more closely mirrors the delayed electrification scenarios by Williams (Delayed electrification) and Princeton (E-) rather than the aggressive electrification scenarios (Central and E+, respectively). An example of this contrast is shown in Figure 17 using NREL's and Princeton's estimated transportation sales. Each of the three studies uses the same model, EnergyPATHWAYS, to represent future electricity consumption of all demand side sectors, but each of those studies incorporate different input assumptions.

C.1 Transportation Demand

In their aggressive electrification scenarios, Princeton and Williams (E+ and Central, respectively) both estimate that nearly all light-duty vehicle sales and a majority of medium-duty vehicle and heavy-duty vehicle sales will be electric early on. They also estimate that most of the operating vehicle stock will be electric by 2050. Some MDVs and HDVs are assumed to run on hydrogen, and a smaller minority still run on gasoline and diesel by 2050. A rapid increase in EV sales begins in the mid to late 2020s in both studies and across all vehicle classes. In the Williams Central case, EV LDVs expand to 50 percent of the market share of vehicle sales by 2030, LDV stock is approximately 75 percent EV by 2030 and reaches 100 percent between 2040 and 2050. Berkeley estimates a more rapid transition to electric vehicles, requiring EVs to be 100 percent of LDV sales by 2030 and 100 percent of MDV and HDV sales by 2035 (see Figure 17).



Figure 17: Transportation sales estimated in electrification scenarios in EFS and Princeton

Note: Note: "EV" includes Battery Electric, "Hybrid" includes Hybrid Electric and Plug-in Hybrid, "Diesel" includes Conventional Diesel, and "Gasoline" includes Conventional Gasoline.

The delayed electrification scenarios of the Princeton and Williams studies (E- and Delayed electrification) and NREL's High scenario estimate more gasoline use by LDVs and more diesel use by MDVs and HDVs in 2050. The greatest expansion in EV sales in these scenarios begins in the 2030s rather than in the 2020s and occurs at a slower pace. For example, Princeton estimates 17 percent of LDVs would be electric by 2030 in the aggressive electrification scenario, compared to 6 percent in the delayed electrification scenario.

It is worth noting that hydrogen has some characteristics that make it an appealing choice for the transportation sector (e.g., rapid fueling for high duty-cycle applications). Furthermore, if hydrogen is adopted widely across the economy to, for example, help decarbonize hard-to-



abate sectors, then the production and use of hydrogen might decrease costs in ways that are not fully captured by the current studies. If that happens, hydrogen fuel cells might see wider adoption beyond just the heavy-duty trucking industry.

C.2 Residential and Commercial Demand

By 2050, Princeton and Williams estimate in their aggressive electrification scenarios (E+, Central) that the residential and commercial sectors will be nearly 100 percent electrified. Space heating and air conditioning needs are supplied mostly by heat pumps—air source heat pumps and ductless mini-split heat pumps for residential and only air source heat pumps for commercial in Williams—and some electric resistance heating. Cordwood stove and geothermal heat pumps are estimated to supply a small portion of residential heating needs. Fossil boilers and radiators, geothermal heat pumps, and natural gas are each estimated to supply a small portion of commercial space heating needs by 2050. This change to electrified heating may shift electric grid peak loads to winter rather than summer (White et al. 2021). Water heating needs are supplied mostly by air source heat pumps and some electric resistance. A small amount of commercial buildings rely on geothermal and residual natural gas use. Cooking needs are supplied by electric resistance appliances, which Princeton notes may include induction stoves. Commercial properties lag residential properties in cooking, in particular where natural gas use persists. Compared to Williams, Princeton estimates a higher level of commercial gas use continuing to 2050. The rapid transition to electrification in the residential and commercial sectors begins prior to 2030 in the two studies. Between 2030 and 2040, in the Princeton E+ and Williams Central scenarios, residential and commercial heating and residential cooking reach 100 percent of sales. By 2050, they reach 95–100 percent of total stock.

EFS high electrification scenario and the net-zero delayed electrification scenarios (Princeton, E-; Williams, delayed electrification) employ the same strategies as the aggressive electrification scenarios, but the transition rate is lower. Princeton E- and Williams delayed electrification scenarios estimate sales of residential and commercial heating and residential cooking approach approximately 95–100 percent by 2050 in the delayed electrification scenarios. Stock is slower to turn over due to delayed sales. By 2050, NREL estimates that residential electric technologies provide up to 61 percent of space heating, 52 percent of water heating, and 94 percent of cooking services in the commercial and residential building sectors combined. Use of gas for heating persists to 2050 in all three studies. By 2050, studies estimate there is still significant commercial sector gas use with delayed electrification. The greatest expansion in sales in these scenarios begins in the 2030s rather than in the 2020s. Williams notes that across all scenarios, heat pumps must reach over 50 percent of market share by 2030 to achieve the level of electrification required for net zero.

C.3 Industrial Demand

Reduction in demand for petroleum in transportation and infrastructure materials such as steel and concrete decrease total industrial energy demand. The electrification of some industrial processes, such as electric boilers and electric arc furnaces for steel production, provides additional gains. Conversely, industrial chemical demand for CCS and DAC technologies may significantly increase industrial final energy demand (Realmonte et al. 2019). Williams highlights that emissions of hard-to-electrify processes are captured or otherwise



offset by negative emissions. Further decarbonization occurs due to switching fuels. Pipeline gas use shifts to renewable natural gas or synthetic fuels, and hydrogen is used for producing ammonia and other chemicals, as well as for processes like direct-reduced iron production. In Princeton, biomass is converted into pyrolysis oils used for petrochemical production. Princeton estimates final energy decreases by approximately 25 EJ by 2050 in the aggressive electrification scenario, a reduction of about 32 percent compared to the Reference scenario mainly due to lower demands for petroleum and pipeline gas and end-use efficiency of electric technologies compared to fossil alternatives. Some electrification changes are assumed to act as flexible demands, consuming abundant, mainly renewable energy at cheaper off-peak times and curtailing during electricity demand peaks.

EFS estimates additional changes to industrial heating, curing, and drying. By 2050, curing is dominated by infrared and ultraviolet heating, some natural gas, and minimal other fossil fuels. Drying is dominated by natural gas but infrared and ultraviolet heating are also utilized. Other process heat is supplied by a plurality of electric resistance, some industrial heat pumps, and minimal induction furnaces along with other fossil fuels. Some boilers switch to electricity, and space heating is dominated by air source heat pumps by 2050. The switch to electric processes is lower and slower in the industrial sector than in other sectors in EFS.

C.4 Demand Response Levels and Altered or Shifted Load

Large flexible demands are integral for enabling the expansion of VRE supply. The value of those flexible demands depends on three things: (1) When is the consumer of energy able to be flexible (e.g., can a manufacturing facility adjust its load during the middle of an afternoon)? (2) Where is the flexible demand located (e.g., is the manufacturing facility near congested transmission lines)? (3) What type of energy does the consumer need (e.g., high energy consumption for short durations versus lower energy consumption for long durations)? This flexibility in demand is particularly important for scenarios with higher levels of electrification. Princeton and Williams pair more renewables on the supply side with more flexible loads, such as electrolysis, electric boilers, DAC, and storage on the demand side. High renewables scenarios require expanded renewable fuels, increasing demand for flexible electrolysis during off-peak times. This hydrogen produced from electrolysis then provides for both industrial uses and firm supply, assuming sufficient storage for the excess hydrogen. Smart charging of electric vehicles and the automation of heat pump systems and water heating provide additional flexibility in demand. EFS does not incorporate the use of hydrogen or DAC, instead relying most highly on flexible loads in the transportation sector followed by the residential sector, industrial sector, and commercial sector in the High electrification scenario where flexible transportation loads are approximately 15 times larger than in the Reference scenario.

C.5 Energy Efficiency

Energy efficiency is assumed in technology upgrades brought on by electrification across all the studies. Choosing the most efficient end-use technologies decreases electricity demand and generation needs, with the potential to reduce total energy system costs. Princeton notes that additional changes could be made to improve building shells and shift transportation from single user vehicles to multioccupancy vehicles, transit, cycling, and walking and from



on-road trucking to rail freight. Increasing fuel efficiency of internal combustion engines will also reduce energy demands and related carbon emissions in vehicles that continue to run on fuels. Energy efficiency is also key in helping the industrial sector decarbonize.

While electrification causes electricity demand to more than double by 2050, strategies such as electric drive trains in vehicles and electric heat pumps for heating in commercial and residential buildings reduce total final energy needed. On the other hand, Williams notes that slow consumer transition to electric vehicles and heat pumps in the Delayed electrification scenario increased fuel demand more than 25 percent relative to the Central scenario by 2050.

Williams also estimates further reductions in energy consumption in the Low demand scenario—the scenario that assumes high rates of energy conservation—reducing consumer demand for energy services such as driving and flying. These changes lower infrastructure requirements and reduce total costs but do not eliminate the need for electrification. Energy efficiency and conservation alone cannot achieve net zero. They must go together with electrification and other decarbonization strategies.

There is a growing body of literature in the energy economics field that empirically estimates the energy savings associated with efficiency upgrades and energy-focused building codes. A key takeaway of this literature is that many of the studies find the realized energy savings from energy efficiency and building codes are well below the engineering estimates (Christensen et al. 2021; Burlig et al. 2020; Fowlie et al. 2018; Allcott and Greenstone 2017; Zivin and Novan 2016; Levinson 2016). Furthermore, these studies provide evidence that at least for weatherization-related energy efficiency upgrades, the overestimated energy savings do not appear to be driven primarily by a rebound effect, meaning more energy use because it is now more affordable (Fowlie et al. 2018). However, the increased efficiency leads to lower costs per unit of energy service and thus a higher quantity of energy services consumed (Christensen et al. 2021; Fowlie et al. 2018). Thus, the assumed energy savings driven by the energy efficiency upgrades in the macro-energy models reviewed may be significantly overstated.

With respect to adoption rates, the economics literature has also described how information asymmetries and lack of cost salience can affect the incentives to invest in energy efficiency upgrades. For example, a long literature explores the “landlord-tenant problem,” whereby asymmetric information between the landlords and tenants with regard to the level of energy efficiency of the rental unit leads to a disincentive for landlords to invest in energy efficiency (Blumstein et al. 1980; Jaffe and Stavins 1994; Gillingham et al. 2009; Allcott and Greenstone 2017; Davis 2011; Gillingham and Palmer 2020; Gerarden et al. 2017; Myers 2020). Furthermore, where energy bills are the responsibility of the tenant, the landlord lacks incentive to make efficiency upgrades while the tenant lacks agency to make property level efficiency upgrades. This dynamic regarding energy efficiency upgrades likely drives the observed reduced energy efficiency of rental units relative to owner-occupied units (Best et al. 2021; Gillingham et al. 2012). These studies indicate that increasing electrification and energy efficiency will likely face barriers beyond simply cost. As such, the level of energy efficiency and/or electrification shown by the macro-energy models using cost-minimizing strategies may be greatly overstated.



APPENDIX D: ADDITIONAL IMPORTANT DECARBONIZATION ISSUES

D.1 Agriculture

The agricultural sector is a source of non-CO₂ emissions such as nitrous oxide (N₂O) from cultivated soils and manure management and methane from enteric fermentation in livestock, accounting for 10 percent of total US greenhouse gas emissions in 2019 (Environmental Protection Agency 2022). Greenhouse gas abatement in the agricultural sector is not a major strategy of most studies, but the Princeton and White House reports put some attention on this area. Princeton evaluates N₂O abatement using cost of CO₂ equivalent emissions to reduce emissions from croplands and livestock by approximately 0.06 gigatons (Gt) CO₂ emissions/year to 2050. The White House outlines mitigation strategies including more use of agricultural and management practices such as cover crops, rotational grazing, manure management, and improved nutrient management, as well as programs that increase productivity that also minimize land requirements. Additionally, the report puts forward advancements in feed additives to reduce methane from enteric sources, as well as replacing synthetic fibers with innovations in carbon-sequestering fiber as future emissions abatement strategies. Changes in diet, such as reduced consumption, including of meat and dairy when practical within health limitations, also have the potential to reduce the environmental impacts of agriculture (Hyland et al. 2017; Garnett 2011; Boehm et al. 2019; Scarborough et al. 2014).

D.2 Carbon Management

Unabated carbon elimination is the main goal of a net-zero future, but the rate at which the US economy decarbonizes varies across studies and scenarios. Some study scenarios show faster emissions declines, and some studies (Princeton, VCE, Williams, EPRI, and the White House) show scenarios that reach net zero. Studies that are not aimed at achieving net zero also show emissions reductions, but they don't get all the way to net zero. The latter do so by reducing fossil fuel use and/or replacing fossil fuels with renewable energy, electrification, transmission, and emissions constraints. While electrification alone has efficiency benefits, it will not achieve net zero by itself; it must also be paired with a net-zero electricity sector (e.g., electric vehicles can improve fuel efficiency, but to achieve net zero the vehicles must receive their electricity from decarbonized sources). Similarly, while transmission expansion allows further expansion of renewable energy generation, it alone does not reduce emissions. As Williams notes, binding emissions reduction policies is the necessary step to push renewable energy, electrification, and expanded transmission further. While electrification and transmission expansion are important improvements to the energy system that can help enable decarbonization, net zero is unlikely to be achieved without sufficient policy commitments.

Decarbonization study scenarios that achieve net-zero emissions employ multiple strategies (e.g., eliminating unabated use of fossil fuels by up to 2,700 TWh from 2020 to 2050 and increasing renewable energy, electrification, and expanding transmission) and fill in the remaining emissions reduction gaps via the use of zero carbon fuels⁹ (e.g., green H₂), CCUS, direct air capture, and expanding land sinks. In general, the timeline of emissions reductions is



faster with more rapid electrification and reduction of fossil fuels, while less CCUS is required to offset carbon emissions.

Most decarbonization and electrification studies report similar trends for timelines of emissions reductions, either on an economy-wide scale or across the electricity sector, as shown in Figure 1. The average rate of emissions reductions economy-wide from 2020 to 2030 is more rapid in the White House report than that of Princeton, Williams, and EPRI's net-zero 2035 scenario. Similarly, the rate of emissions reductions in the electricity sector from 2020 to 2030 in VCE's clean economy and clean energy by 2035 scenarios is more rapid than that of EPRI, Berkeley 2035, and EFS.

D.2.1 Carbon Management Strategies

Carbon can be captured, utilized, and sequestered in a variety of ways to help accelerate decarbonization, even in a scenario in which the economy continues to emit GHGs. These methods include land sinks, mineral weathering, forestry, DAC, and CCUS, which will be collectively described as carbon management strategies. These strategies help achieve net-zero emissions, but none of the studies under consideration deploy them as a primary solution to decarbonize. Instead, carbon management strategies are intended to supplement other broader pathways to decarbonize, including expanded electrification while reducing the impact of sectors in the economy that are otherwise hard to decarbonize. Overestimation of the capability of land sinks, DAC, and CCUS can lead to increased emissions (Realmonte et al. 2019).

The net-zero studies do not extend the life of carbon-intensive sectors that have viable alternatives. For example, none of the studies incorporate carbon capture with coal-fired electricity generation—consistent with global literature and the recent IPCC AR6 reports. Carbon management strategies are instead paired with carbon-intensive sectors that cannot be easily eliminated. For example, Princeton and Williams incorporate carbon capture in the hard-to-electrify cement and steel industries. Some studies, for example VCE and Berkeley 2035, attach carbon capture to continue natural gas generation, particularly when the scenario includes delays in natural gas reduction due to other constraints. In addition, constraining land use limits biomass, renewables, and transmission and can result in increased fossil fuel use. EFS meets its emission constraint with carbon capture attached to natural gas generation. Princeton pairs carbon capture with biomass generation or gasifying biomass to form hydrogen for a net negative emissions technology.

DAC and land sinks are used to offset any lingering fossil fuel use (e.g., the gas used for cooking in the commercial sector). Higher DAC compensates for lower electrification, constrained renewable energy, and low natural gas prices. DAC is an expensive technology, and inputs needed for its operation may be constrained by industrial capacity, limiting DAC scalability (Realmonte et al. 2019).

Captured carbon may be used for producing synthetic fuels, but sequestration is generally more favorable, unless a scenario requires more renewable energy or CCUS costs are low. Both utilization and storage of carbon require expansion of carbon transport infrastructure such as pipelines.



Land sinks, including carbon uptake in soils and trees, provide additional natural capture and storage in the Princeton, Williams, and White House studies. The White House points out opportunities in integrating trees into urban areas and increasing and protecting forested areas, including efforts to reduce wildfires and restore fire-damaged land. However, Princeton notes that land availability will limit carbon capture and storage via land sinks. Additionally, climate change may limit availability of carbon sinks in the future. Friedlingstein et al. 2021 estimate climate change reduced land sinks by about 15 percent from 2011 to 2020. Furthermore, it is possible to overestimate land sink carbon offset capabilities (Song and Wang 2021; Gundersen et al. 2021; Randerson et al. 2009). Thus, care must be taken in the accounting for such benefits in practice.

D.2.2 Carbon Management Timeline

Decarbonization studies and scenarios employ varying amounts of the above strategies to achieve net zero either economy-wide or in the electricity sector. Princeton, Williams, the White House, and EPRI show economy-wide changes, while EPRI, VCE, Berkeley 2035, and EFS show electricity sector changes. In Princeton's study, geologic sequestration is required at varying levels to offset continued use of fossil fuels except in the increased renewable energy (E+RE+) scenario. More sequestration—over 1.5 billion metric tons by 2050—is required when renewables are constrained (E+RE-). This requirement is due to the expansion of natural gas compared to other electrification scenarios and the continued use of diesel and gasoline, as well as jet fuel and other residual petroleum. The delayed electrification (E-) and increased biomass with delayed electrification (E-B+) scenarios also rely on nearly the same amount of geologic sequestration due to slower transition away from primary fuel use and more use of diesel and gasoline compared to other electrification scenarios. The speed of electrification and choice of energy sources have large impacts. Decisions on siting, generation technology, pollution abatement, and electrification rate also impact air quality, such as the exposure to fine particulate matter, which often disproportionately impacts lower income populations.

In Williams, all cases reach net zero by 2050. The expanded renewable scenario (100 percent renewable primary energy) and the Net negative scenarios go further than net zero and reach negative emissions. Most cases emit a cumulative 79 GtCO₂ from 2020 to 2050, versus 138 GtCO₂ in the reference scenario. The 100 percent RE case reaches 75 GtCO₂, and the Net negative case still reaches 73 GtCO₂ cumulative emissions. The cumulative emissions are due mainly to the sustained use of oil and natural gas, as well as the lingering effect of burning coal through the 2030s and other industrial processes. Emissions are offset in each scenario by a combination of product sequestration and geologic sequestration. Product sequestration remains the largest offset strategy in all scenarios. Geologic sequestration is not used in the 100 percent RE scenario but is relied on in the Central, Low fuel price, and Delayed electrification scenarios due to expanded fossil fuel use, the Low land scenario due to constraints on renewable energy, and the Net negative scenario to accelerate the timeline to achieve net zero. In the study, achieving net zero while continuing fossil fuel use is not possible without carbon capture, specifically higher sequestration and lower utilization of carbon. More synthetic fuel use also requires carbon capture as it is the basis for fuel synthesis. Synthetic fuel use enables lower sequestration and higher utilization of carbon.



The White House report shows major emissions reductions due to transforming the energy sector through energy transition to hydrogen, low-carbon fuels, and electrification (approximately 2.5 GtCO₂); decarbonizing electricity with zero carbon generation and fossil fuels with carbon capture and storage (approximately 1.5 GtCO₂); and energy efficiency in transportation, buildings, and industry (approximately 1.25 GtCO₂) compared to 2005 when domestic emissions were at or near an all-time high. Additional reductions of less than 1 GtCO₂ each are attributed to land sinks, carbon removal technologies, and non-CO₂ reductions in fluorinated gases, N₂O, and CH₄. Emissions vary by scenario with electricity sector reductions occurring most rapidly, reducing approximately 0.75 to 1.25 GtCO₂ by 2030 and another approximately 0.25 to 0.5 GtCO₂ by 2040. Transportation sector emissions reductions occur most rapidly between 2030 and 2050, reducing by approximately 1.25 GtCO₂ over the two decades. Industrial and building sector emissions are reduced by approximately 0.5 to 1 GtCO₂ and 0.25 to 0.5 GtCO₂, respectively, by 2050. While the White House analysis uses an earlier start date than other studies, the absolute reductions across other economy-wide carbon reduction evaluations in Williams and Princeton are similar.

EPRI shows emissions estimates for a select set of scenarios: the Net Zero 2035 scenario and the economy-wide carbon price with and without negative emissions. The Net Zero 2035 scenario achieves a reduction in the annual economy-wide emissions of over 4 GtCO₂ from 2005 to 2050, with the electric sector itself achieving approximately 1.5 GtCO₂ reduction in annual emissions by 2035. The economy-wide carbon price scenario without negative emissions achieves a more rapid reduction of approximately 1 GtCO₂ in the electric sector by 2025. However, the reduction immediately slows, and overall electricity sector CO₂ reduction is slightly less than those of the Net Zero 2035 scenario. When negative emissions are included, the rapid reduction of 1 GtCO₂ is instead followed by continued abatement for a total reduction of approximately 2 GtCO₂ in the electric sector and nearly 5 GtCO₂ economy-wide.

VCE evaluated the emissions impact from energy sector changes on CO₂, carbon monoxide, SO₂, nitrogen oxides (NO_x), CH₄, N₂O, volatile organic compounds (VOCs), and particulate matter at 2.5 and 10 micrometers (PM2.5 and PM10, respectively). VCE compared the emissions impact based on projected reductions to the starting year, 2018. The fastest and largest reductions occur in PM2.5, PM10, and N₂O, and the slowest reductions are in CO₂ and CH₄ across their scenarios. In the EBAU scenario, reductions plateau by 2035, ranging from 40–100 percent of the 2018 value for each pollutant. In EBAU-, a scenario that delays economy-wide decarbonization changes compared to EBAU, reductions peak by 2035, but pollution increases by 2050 for five pollutants. The four expanded transmission scenarios that prioritize both 100 percent clean economy by 2050 and clean electricity by 2035 (ECE HVDC-, ECE HVDC*, ECE HVDC-, ECE HVDC+) show 100 percent reduction of all pollutants by 2035. The scenarios that prioritize 100 percent clean economy but do not include clean electricity by 2035 (ECE*, ECE, and ECE HVDC) show major emissions reductions by 2030–2035, but they do not achieve 100 percent reductions until 2050.

In Berkeley 2035, the 90 percent clean scenario reduces CO₂ emissions by 1.3 GtCO₂ from 2020 to 2035, compared with the reference case, an 88 percent reduction. It also reduces PM2.5 exposure and NO_x and SO₂ emissions by 96 percent and 99 percent, respectively. It should be noted that Berkeley assumes greater use of coal in the reference scenario than any



other study and thus shows increased comparative benefits due to its removal.

EFS shows reductions in CO₂, SO₂, and NO_x emissions in the high electrification scenario compared to reference, with the greatest reductions in transportation sector CO₂ and NO_x emissions. In the high electrification scenario, total CO₂ is reduced by approximately 1.5 billion metric tons from 2018 to 2050. However, the electricity sector shows increased CO₂ emissions due to electrification without transition from fossil fuels. No pollutant is reduced to zero across scenarios. NREL's Seams does not show emissions reductions. They are incorporated into costs but not explicitly stated.

D.3 Jobs

The models suggest decarbonization will lead to job growth that exceeds the job losses associated with the energy transition. Job growth is expected mainly in the solar, transmission and distribution, wind, and energy storage industries. The highest change in induced and direct jobs is expected in 2035. The studies differ in the scale of job growth, with VCE expecting more jobs than Princeton. Princeton estimates that the supply side energy workforce expands by over 30 percent between 2020 and 2030 for an annual average of approximately three million jobs and then nearly triples by 2050. The number of jobs in the supply side energy sector grows from approximately 1.5 percent of the labor force in 2020 to 2–4.5 percent by 2050, depending on the scenario. Wages also increase by \$30–\$40 billion over the reference scenario for a total of approximately \$180–\$190 billion in wages between 2020 and 2030. Princeton expects most states to see energy-related employment growth. However, states with high shares of current labor force employment in upstream fossil fuels do not necessarily see energy-related employment growth. Scenarios that rely on more renewables or alternative technologies see more job increases than the others. Coal jobs decrease in all scenarios, but natural gas jobs increase when natural gas capacity increases. Nuclear jobs increase when advanced nuclear capacity increases. In Berkeley's 90 percent clean scenario, energy sector-related employment increases by approximately 8.5 million net job years to approximately 29 million job years total from 2020 to 2035, a two-thirds increase over the reference scenario. Despite declines in the fossil fuel industry, each of the relevant studies projects that job growth is expected to exceed jobs lost across the economy.

With all macro-energy models, formulation of job “creation” and “loss” must be evaluated. In its simplest form, jobs are typically added (or reduced) in MES models at a constant rate per unit of physical capital installed. For example, jobs will be “created” at a certain rate per kilowatt of solar capacity installed. This abstracts from the way job creation is considered from the economics perspective in several key ways that can lead to an overstatement of the job additions in the MES models discussed. In a very simplistic framing, dynamic macroeconomic models show increased productivity leads to an expansion of the economy and thus an expansion in employment. To assume that increased investments to enable electrification and clean energy will yield increased productivity is to assume that the lower levels of investment in energy infrastructure under the business-as-usual case is due to some market failure that disincentivizes firms and individuals from making the investments seen under a net-zero path. While some of these market failures likely exist (e.g., the landlord-tenant problem), it's unlikely that correcting all these market failures incentivizes the level of



investments needed to be on a net-zero path. Second, the assumption of a constant rate of job addition per unit of installed capital does not account for any labor market equilibrium effects. For example, policies that promote the expansion of renewable energy capacity (e.g., the ITC) increase the demand for skilled labor that is needed to meet that expansion goal. This increase in labor demand increases wages for skilled labor, which increases costs in other industries that also require skilled labor, lowering the quantity demanded in these sectors and creating essentially a job shuffling of sorts, where jobs decrease in the nonclean energy sector and increase in the clean energy sector (Borenstein 2017).¹⁰ Similarly, the financing of the policies to expand clean energy and/or increase electrification likely requires increases in taxes or increases in general energy costs. These tax and/or energy cost increases have their own general equilibrium effects that reduce demand in ways that likely lower employment in other sectors.

These general equilibrium effects, where the policies aimed at a specific sector create cost and price effects in other sectors, are more directly captured in the computable general equilibrium (CGE) models in economics than in the MES models discussed here. Many CGE models have been created to explore economy-wide labor and output effects of climate policy, particularly carbon taxes (see Wing 2009, for a review). While these CGE models include detailed linkages across multiple sectors in an economy, and potentially across many different regional economies, they often lack the detailed modeling of the energy and transportation sectors included in the MES models examined here. More accurately portraying the employment effects of the energy and environmental policies needed to reach the net-zero goals will require building links between these sectoral diverse CGE models that are rooted in microeconomic principles and the detailed energy sector representation found in many of the MES models (Glynn et al. 2015 “Global”; Glynn et al. 2015 “National”).



APPENDIX E: ABBREVIATIONS

CCGT: combined cycle gas turbine

CCUS: carbon capture, utilization, and sequestration

CSP: concentrated solar power

DER: distributed energy resources

H₂: hydrogen

LSE: load serving entities

MES: macro-energy system

MSR: molten salt reactor

NGCC: natural gas combined cycle

NGCT: natural gas combustion turbine

PV: photovoltaic

SMR: small modular reactor

VRE: variable renewable electricity



NOTES

1. Novel technologies (e.g., natural gas with carbon capture and sequestration, small modular reactors, molten salt reactors, and enhanced geothermal systems) are set to be 40 percent of a mature technology, but their installation dates are pushed into the future so that they cannot be installed before a set investment period.
2. Net zero, in this case, refers to removing, reducing, and offsetting carbon dioxide emissions under the control or territorial responsibility of the United States such that the effective total is zero (definition adapted from Grubb et al. 2022).
3. See Bednar and Reames (2020) for a more thorough description of the evaluation of and policy response to energy poverty in the US.
4. Per Williams, “Total energy spending includes all investments in supply side energy infrastructure, fuels, and operations and maintenance, and incremental costs of demand side equipment relative to their equivalent reference investment in the Reference scenario.”
5. Thus, all references to “solar” in this study are referring to solar PV.
6. Additional studies on specific policy or research changes have recommendations that concur with the prior studies that were the focus of this report, including: Hultman et al. 2021, Lempert et al. 2019, Davis et al. 2018, Kennedy et al. 2021, and Elsevier Analytical Services 2021.
7. Lempert et al. (2019) recommends incentives for afforestation or reforestation and “carbon farming” practices that increase sequestration in soils.
8. Modeled locations are scenarios, not recommend locations for installation.
9. Fuel, here and elsewhere in this manuscript, refers to a combustible substance used as an energy source. It does not refer to energy sources generally. Thus, a zero-carbon fuel here would not refer to solar or wind.
10. One may argue that such job shuffling described here can only result in scenarios where there is no unemployment. Currently, the US is in such a period of low unemployment, so the scenario is relevant. Additionally, even in periods of high unemployment, skilled labor unemployment rates often are lower than the economy at large. In periods of considerable slackness in the labor market, economists generally agree that some stimuli, including energy investments, is warranted. However, as those periods are transitory, it is unlikely that slack labor conditions will persist over the period needed to reach net-zero goals.



The CHAIRMAN. Thank you.
Mr. Tudor.

**STATEMENT OF DAVID J. TUDOR, CHIEF EXECUTIVE OFFICER
AND GENERAL MANAGER, ASSOCIATED ELECTRIC COOPER-
ATIVE INC.**

Mr. TUDOR. Good morning, Chairman Manchin, Ranking Member Barrasso, and members of the Committee. Thank you for the opportunity to testify today on the threats to electric reliability and affordability. This is a growing threat that I believe will have dire consequences for the American people and also creates a national security risk. My name is David Tudor. I am the CEO of Associated Electric Cooperative, based in Springfield, Missouri. We are a member-owned, member-led, not-for-profit, wholesale electric utility that delivers power to 2.1 million mostly rural people in Missouri, Oklahoma, and Iowa. Associated Electric and its six transmission cooperative owners operate 5,700 megawatts of generation capacity and over 10,000 miles of transmission to serve 51 distribution cooperatives that are owned by the 2.1. We are not a regional transmission organization, an RTO. In the RTO, the utilities pool their resources to serve their shared load. We have chosen to remain independent, which makes us fully responsible for serving our member-owners. However, we have over 200 interconnects with SPP, MISO, and TVA. Associated Electric kept the lights on during Winter Storms Uri and Elliot when our neighboring utilities were forced into rolling blackouts.

I am honored to be given this opportunity to testify today, and I have submitted extensive written testimony with actual data from our experience. I believe I was invited today to share with you how we kept the lights on when others couldn't, and the challenges we are now facing in continuing to do so. Let me start with my seven primary concerns. First, coal plants are being prematurely retired. According to EIA data across the country, 86,000 megawatts have been retired since 2011. An additional 73,000 megawatts have been announced to be retired by 2028. The new EPA rules, announced two weeks ago, will likely lead to more retirements despite the legal challenges that will be filed. Second, there is no technology to deliver around-the-clock, baseload electricity to replace this retired generation. It has to be tested, proven, financeable, and also connected to the transmission grid by 2028, when all these coal plants are retired. In fact, it is doubtful anything will be ready by 2035.

Third, the queue, which has been spoken about this morning for new replacement generation in MISO, SPP, and PJM, is largely made up of intermittent resources—wind, solar, and battery storage. Only three to four percent is natural gas, a dependable resource. Fourth, these queues have major problems, in that each generator site must be studied for system impact effects and the cost to upgrade the transmission system to accept them into the grid, all before work could even be started. Fifth, new transmission takes four to six years to build, if the materials can be procured timely. The materials cannot, today, be procured timely. Transformers, conduits, and poles have their own queues. Sixth, the cost for new transmission continues to climb due to inflation and supply

chain challenges. Seventh, maybe most important, China and other countries continue to build coal plants while we are forcing ours to retire. It's the same air.

Associated has chosen a path less traveled because we use data and experience to make business decisions. I want to be clear—we are not against renewables. I want to be clear also that we need all generation resources to keep the lights on. We do not pick arbitrary success dates on projects or make soft promises to retire a plant at a future date. We do not retire plants that are environmentally compliant without a real alternative that is reliable and affordable. Our members expect us to keep the lights on. We survived storms Uri and Elliot because we have a balanced portfolio of coal, natural gas, hydro, and wind. Our data proves that without our coal, natural gas, and hydro plants we would have incurred blackouts during both storms. Out of the 1,240 megawatts of wind that we have, we had only 179 megawatts at our peak of Uri and only 552 megawatts during Elliot. That is less than 45 percent. We set 13 new all-time peaks during Elliot. Our fossil fuel plants and our independent transmission system saved the day.

So what is the solution? The three T's—technology, transmission, and time. The technology will develop. The transmission can be built. We just need more time. We need to get control of the EPA, who doesn't seem to care about reliability or cost. We need to cut the red tape on permitting on all generation, transmission, and pipeline projects. And we need to use these IRA funds to find that technology we need so badly.

In closing, this desire to put climate change objectives ahead of reliability in the United States is a risk not worth taking. It's not too late for you to take action. Thank you for having me today.

[The prepared statement of Mr. Tudor follows:]



Testimony of David J. Tudor
Chief Executive Officer
Associated Electric Cooperative Inc.

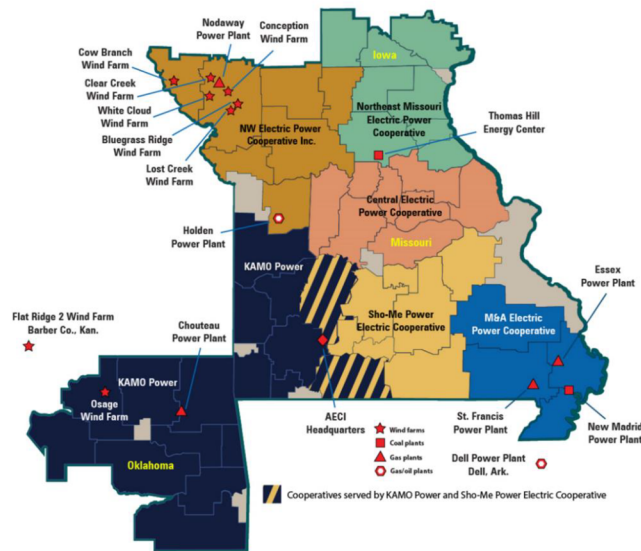
United States Senate Committee on Energy and Natural Resources
*"Hearing to Examine the Reliability and Resiliency of Electric Services
in the U.S. in Light of Recent Reliability Assessments and Alerts"*

June 1, 2023

Chairman Manchin, Ranking Member Barrasso, and members of the Committee: thank you for the opportunity to testify here today.

Associated Electric Cooperative Overview

Associated Electric Cooperative (Associated) is a member-owned, member-led wholesale power generation and transmission cooperative created in 1961 by rural electric cooperatives to provide electricity reliably and affordably for rural areas of the Midwest. Today, this system delivers electricity to 935,000 meters (each meter equals one member-consumer), representing 2.1 million people across rural Missouri, northeast Oklahoma and southeast Iowa. Associated's member-consumers are primarily older, lower income electricity users who live in rural parts of the three-state system. More populous urban and suburban areas of these regions are served by municipal or investor-owned electric utilities.

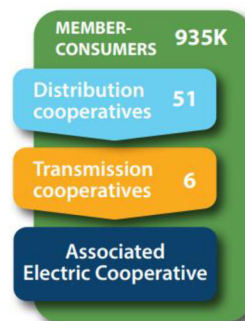


map: AECI.org



Associated is a system comprised of three distinct tiers, each specializing in one critical area of the electric utility process and accountable for its performance through democratic control at every tier.

- **Generation:** In the first tier, Associated generates power for six regional transmission cooperatives who are member-owners of Associated.
- **Transmission:** In the second tier, the six regional transmission co-ops use an extensive network of substations and high-voltage power lines to deliver the power to 51 distribution co-ops who are their member-owners. Associated and its six transmission co-op owners own and operate 10,288 miles of transmission lines.
- **Distribution:** The third tier is made up of the 51 local power co-ops that deliver electricity to member-consumers at homes, farms and businesses in rural areas. 935,000 member-consumers served by this distribution tier own and are democratically represented at their local co-ops.



The system is independent of regional transmission organizations (RTOs) and makes decisions as a not-for-profit entity, but in the best interests of members who are also owners. Associated features more than 200 interconnections with Regional Transmission Organizations (RTOs) and others, which through its independence and focus on members, enables transactions to support reliability and keep members rates lower than they otherwise would be.

Member surveys of Associated's member-consumers reveal they are relatively: older, with 57% over the age of 57 and 33% over the age of 65; retired, with 34% retired and 54% employed full-time; and lower income, with 50% of household incomes less than \$100,000 annually and 22% of less than \$50,000. Escalating prices for electricity are regressive, impacting those most who are least able to afford to pay more. For many years, Associated's wholesale power rates to its member have been among the most affordable in the nation and continue to be today.

Associated's evolving resource portfolio

Associated has developed a balanced generation portfolio comprised of on-demand, dispatchable generation and intermittent renewable sources. Since 2005, Associated's generation portfolio has changed to include significant amounts of natural gas and contracted wind power, complementing coal, federal allocations of hydropower and purchases from the RTO markets.

This owned and contracted power provides a total generating capacity of 5,626 megawatts (MW). This includes over 2,300 MW of coal and has evolved over time to include nearly 2,800 MW of natural gas and significant wind resources. Associated contracts with eight wind farms totaling 1,240 MW of nameplate capacity. Because of its intermittent nature, wind energy is not included as capacity for planning purposes. Associated also receives nearly 500 MW of hydropower from the Southwestern Power Administration.

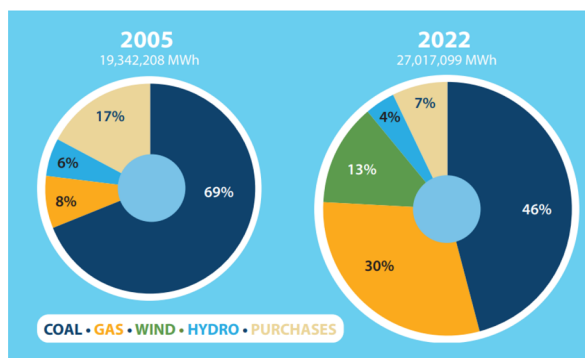


chart: AECI 2022 annual report

Technology, transmission and time necessary for an energy transition that preserves reliability

Associated believes that for a transition to a reliable energy industry future with lower emissions, all policies need to consider the maturity of technology and the time it takes to build new generation and transmission lines under the current regulatory and RTO paradigms. Three key areas must be addressed to make sure reliability is not a casualty of the transition:

- **Technology:** Potential solutions are being studied that may one day provide reliable, affordable, and zero-emission power for member-consumers. It is not a reality today or near-term. No commercially available technologies can replicate the reliability of a dispatchable coal, natural gas, or nuclear power plant.
- **Transmission:** Roadblocks can only be addressed with expensive and extensive upgrades to the existing transmission system. Those upgrades will take several years, and some may take over 10 years to complete under current regulatory paradigms and supply chain challenges.
- **Time:** Both new technology development and transmission system upgrades need time to mature and be implemented effectively. Natural gas units are the only viable bridge generating source available today.

Overview of Reliability Assessments

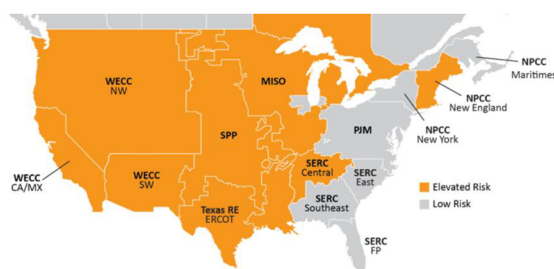
As electric cooperatives work to meet the changing demands of our communities and our member-consumers, reliably keeping the lights on is vital for the health and wellbeing of those communities, the economy, and national security. Unfortunately, that obligation is becoming more and more challenging.

The 2023 Summer Reliability Assessment issued last month by the North American Electric Reliability Corporation (NERC) found that more regions of the U.S. than in 2022 face elevated risks of electricity supply shortfalls during periods of extreme summer weather. Although the 2023 Assessment did not identify any regions as high-risk, only under normal summer conditions is the entire country expected to have adequate power resources. The key findings by NERC on the reasons for these reliability challenges



this summer are consistent with its *2022 Long-Term Reliability Assessment* and other assessments and reports.

Summer Reliability Risk Area Summary

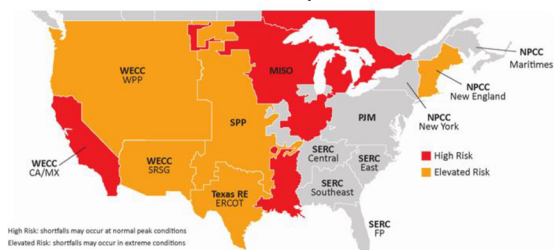


map: 2023 NERC Summer Reliability Assessment

Importantly, the 2023 NERC summer reliability assessment is just the latest in a series of alarming reminders about the new electric reliability challenges facing the nation. Earlier this month, Federal Energy Regulatory Commission (FERC) Commissioner Mark Christie warned this Committee of threats to reliable electricity, stating “I think the United States is heading for a very catastrophic situation in terms of reliability.” In March, PJM Interconnection CEO Manu Asthana said that the RTO needed to slow the pace of generation retirements to avoid reliability problems by the end of the decade. “I think the math is pretty straightforward,” Asthana said. And ISO New England has struggled to meet winter demand for over two decades. While the region has avoided blackouts to date, the grid operator “attributes that streak largely to luck.”

Likewise, NERC’s long-term assessment for the next decade shows Associated’s service area surrounded by areas of high and elevated risk for reliability problems.

Risk Area Summary 2023–2027



map: 2022 NERC Long-Term Reliability Assessment

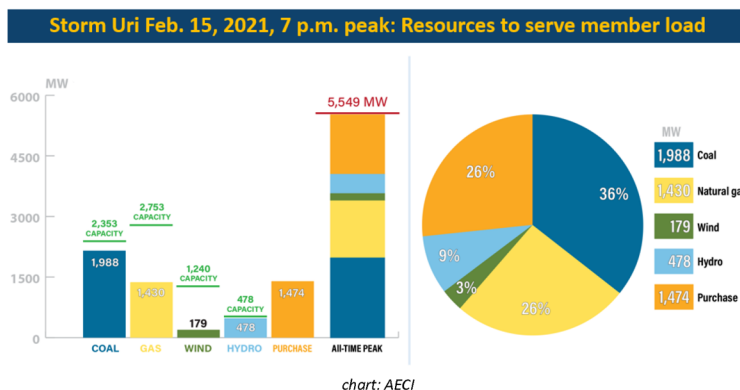


Recent Associated history: real-world proof diverse generation sources deliver reliable electricity

2021 Winter Storm Uri: A balanced generation mix kept power flowing to the rural Midwest

Settling in the weekend of February 13, 2021, winter storm Uri impacted a large part of the country, bringing into question the reliability of the bulk electric system. In its service area, Associated experienced temperatures as low as –20 F, with wind chill readings of –40 F at its northernmost plant. The RTOs of ERCOT, MISO and SPP implemented rolling blackouts. Millions of customers lost power, and over 700 lives were lost due to the severe cold and blackouts in Texas. The storm taxed transmission facilities, natural gas processing facilities and gas supply. Natural gas and energy prices skyrocketed. Gas in Oklahoma, for example, settled at a historic high February 18 at \$1,193/MMBtu. Although the Associated system set its three highest all-time peaks at that time, a balanced generation mix kept power flowing throughout the storm with no rolling blackouts.

The key: Associated relies on a balanced generation mix, with proven and reliable coal and natural gas generating plants as a valuable foundation for reliability and dispatched its units to full capacity in advance of the cold temperatures. Despite significant outside pressure in recent years to move to other options, these fossil-fuel generating stations were the major factor in keeping the lights on for the 2.1 million people we serve. Hydropower allocated by the Southwestern Power Administration was a reliable energy source. Wind generation in Associated's mix played a minor role during the storm.

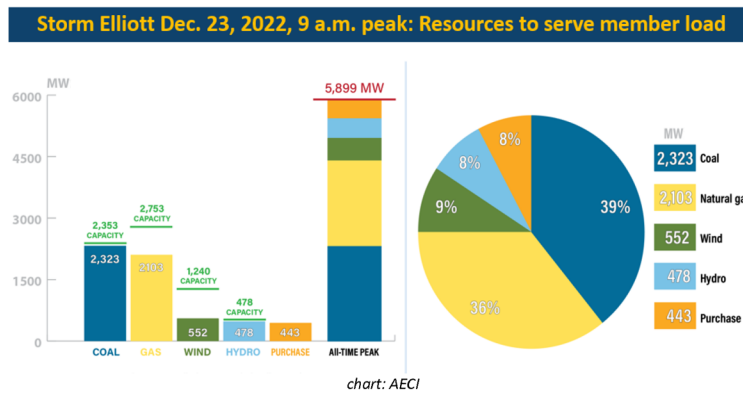


2022 Winter Storm Elliott: New all-time peak, balanced generation mix maintain reliability

From December 22 to 23, 2022, the Associated system faced the brunt of winter storm Elliott that brought brutal cold, wind and snow to the Midwest. Across much of Associated's service territory, wind chills reached –35 degrees with 50-plus mile per hour wind and snow. Associated kept the power on as a new all-time peak was set, then set again in less than 24 hours. On December 22, the previous record was bested with a 5,809 megawatt peak for the hour ending at 8 p.m., only to be surpassed December 23 by a new all-time 5,899 MW peak for the hour ending at 9 a.m.



The key: Associated's ability to ensure reliability during the historic cold snap was the generation fleet's balanced and diverse portfolio. During the 9 a.m. peak hour December 23, Associated met most member load with its resources, generating 2,323 MW from coal plants; 2,103 MW from gas plants; 552 MW from contracted wind energy and 478 MW from hydropower. The remaining load was met by purchases across firm transmission line pathways. Associated's wind resources provided a moderate, but important, amount of power during the peak. Again, coal and natural gas generation carried the day, preserving reliability for Associated's members when they needed power the most.



Five Issues Impacting Reliability and Affordability

Today's energy decisions will determine if there are enough resources to meet tomorrow's energy needs. As noted earlier, policymakers must recognize the need for time, technology development, and new transmission infrastructure before taking our nation down an energy path that prioritizes speed over successfully keeping the lights on. And lawmakers must support policies that are inclusive of all energy sources to maintain reliability and affordability. Rolling blackouts cannot become the new normal in America.

The National Rural Electric Cooperative Association (NRECA) has identified five of the greatest issues impacting energy reliability and affordability, which is supported by findings from NERC's reliability assessments and by Associated's own experience.

"Disorderly" Retirement and Insufficient Replacement of Always Available Generation

The disorderly retirement of existing generating assets, and insufficient supply of readily dispatchable replacement generation, has directly jeopardized reliability. Many generating assets taken off-line in recent years have been replaced with sources providing less capacity, no capacity, or capacity that is intermittent and not always available. NERC has warned that for many regions of the country, the additional retirements of baseload thermal power plants – if not replaced by dispatchable, flexible



resources – will increase risk of rolling blackouts.¹ As NERC correctly points out, “merely having available generation capacity does not equate to having the necessary reliability services or ramping capability to balance generation and load.”² NERC recommends that policymakers and industry manage the pace of generator retirements until solutions are in place to meet energy needs and ensure reliability.³

The accelerated pace of retirements of on-demand, dispatchable coal generation in particular will put reliability in serious jeopardy, with 86,000 MW retired since 2011 and another 73,000 MW in announced retirements projected by 2040. Of those retirements, MISO and SPP, the RTOs contiguous with Associated, have retired 23,000 MW of coal generation and announced another 26,000 MW of retirements by 2040, with most retiring by 2028. Non-dispatchable, intermittent wind and solar generation comprise the majority of the MISO and SPP generation additions projected for the future. In MISO, the future generation interconnection requests are mostly solar and wind comprising 64% of new generator requests; natural gas only 3%. In SPP, solar and wind comprise 68% of new generator requests; natural gas only 4%. Trading on-demand dispatchable generation resources for intermittent, non-dispatchable resources will only exacerbate the reliability problem for years to come. Until a reliable source of new generation—a technological breakthrough—becomes available and financeable on a wide scale, the degradation of electric reliability will continue to worsen, putting our nation at risk.

Unfortunately, the pace of reliable, baseload generation retirements will accelerate under overly aggressive and unworkable federal environmental regulations. NERC has identified the Environmental Protection Agency’s (EPA) final ozone transport regulations, which would limit the operation of coal-fired generators in 22 states, as one of the key reliability issues for grid operators to watch this summer.⁴ PJM warns that the combined effects of that ozone regulation, effluent limitation guidelines and coal combustion residuals regulations and state policies could result in a significant amount of generation retirements within a condensed time frame.⁵ EPA’s latest proposed rule to regulate new and existing power plant carbon dioxide emissions could further disrupt domestic energy security, force critical always available power plants into early retirement, and make new natural gas plants exceedingly difficult to permit, site, and build. Given the significant economic and operational implications of this proposed rule, EPA should extend the current 60-day comment period by at least an additional 60 days to ensure there is adequate time to fully evaluate and comment on this proposal. And we urge EPA to strongly consider the concerns that will be expressed in the submitted comments.

EPA has indicated that their goal is to issue all of these power sector regulations in a coordinated way to encourage the closure of coal and natural gas units. Yet it has not provided sufficient time to analyze and comment on these complex, compounding and interrelated regulations. Department of Energy (DOE) Secretary Granholm and EPA Administrator Regan in March of 2023 signed a Memorandum of Understanding on electric sector resource adequacy and reliability coordination, with a shared objective of supporting the continued delivery of “a high standard of reliable electric service.” Achieving that

¹ North American Electric Reliability Corporation. *2022 Long-Term Reliability Assessment*. December 2022. https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2022.pdf

² *Ibid*

³ *Ibid* at 7.

⁴ North American Electric Reliability Corporation. *2023 Summer Reliability Assessment*. May 2023. https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_SRA_2023.pdf

⁵ PJM Interconnection. *Energy Transition in PJM: Resource Retirements, Replacements & Risks*. February 24, 2023. <https://www.pjm.com/-/media/library/reports-notices/special-reports/2023/energy-transition-in-pjm-resource-retirements-replacements-and-risks.ashx>



objective is impossible, given the impractical timeframes for commenting on these regulations. It is imperative that NERC, RTOs/ISOs and other reliability entities, in coordination with DOE and power companies and relevant trade associations, have the opportunity to evaluate the collective impact on reliability of all EPA's so-called "suite of regulations" for coal and natural gas power plants.

Electrifying the Economy

As a nation, we are trending toward a future that depends on electricity to power more of the economy. The electric sector is poised to play a major role in transforming and reducing emissions in the transportation, industrial, agricultural, and other sectors through increased electrification. However, the increasing role of electrification will place even more demands on the electric grid and generation portfolio and will require measures to enhance grid reliability and to keep costs affordable. Electrifying other sectors of the economy will require a three-fold expansion of the transmission grid and up to 170% more electricity supply by 2050, according to the National Academies of Sciences.⁶ And recent modeling by the Electric Power Research Institute finds that achieving net-zero economywide emissions by 2050 could require generation capacity to increase by as much as 480% compared to what is in place today.⁷

This movement toward greater economywide electrification will require tremendous planning, investment, and collaboration among all stakeholders. Electric co-ops and other utilities must be involved from the beginning, particularly with electric vehicle infrastructure buildout, to ensure they can continue to provide safe, affordable and reliable power. And as NERC emphasizes, industry and policymakers must consider and account for the impact increased electrification will have on future electricity demand and infrastructure as we plan to meet tomorrow's energy needs.⁸

Finally, in the context of economywide electrification and load management, it should be noted that co-ops have long been utilizing and encouraging energy efficiency programs in their service territories. Electric co-ops want to keep power as affordable as possible, which is more attainable with less energy demand. For example, Take Control & Save, a suite of energy efficiency services and rebates funded by Associated and its member systems, provides significant financial incentives for member-consumers to save energy. In a win-win for Associated and its member systems, Take Control & Save offers 15 rebates to improve energy efficiency across the system, helping families save money on heating and cooling equipment, smart thermometers, weatherization improvements, residential energy audits and more. Associated benefits by generating less energy than it otherwise would during periods of peak use and the program was recently extended through 2025. To help us expand the use of these load-management tools, we encourage Congress to support and maintain policies that enable our co-op members to take full advantage of energy efficiency upgrades and rebates.

⁶ National Academies of Sciences, Engineering, and Medicine. 2021. *Accelerating Decarbonization of the U.S. Energy System*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/25932>.

⁷ Low-Carbon Resources Initiative. *Net-Zero 2050: U.S. Economy-Wide Deep Decarbonization Scenario Analysis* <https://lcri-netzero.epri.com/>

⁸ North American Electric Reliability Corporation. *2022 Long-Term Reliability Assessment*. December 2022. https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2022.pdf



Permitting Challenges

As we strive to meet the nation's growing energy demands and our member-consumers' expectations for reliable and affordable electric service, co-ops will need to build significant amounts of new electric transmission and generation capacity of all types. The current environmental review and permitting process required to build, site, and maintain electric infrastructure is outdated and a significant impediment to meeting tomorrow's energy needs.

For example, the timeframe for permitting new natural gas plants has been lengthened significantly. From start to finish, including permitting, the previous generation of Associated's natural gas peaking units were online in about three years. Today, permitting alone for new units will likely take about three years, extending the completion of the units to six to seven years. Many of the projects electric co-ops will undertake will need to navigate federal, state, and local environmental permitting processes. For major generation and transmission projects, this will likely include a National Environmental Policy Act (NEPA) Environmental Impact Statement (EIS). Unfortunately, as just one indicator of the headwinds we currently face, it takes an average of 4.5 years to complete an EIS and issue a permitting decision. One quarter of EISs take more than 6 years. Those timelines do not include any litigation that may further prolong the process.⁹ This is simply too long.

We applaud Congress's inclusion of critical NEPA modernization provisions in the bipartisan debt ceiling agreement being considered this week. These reforms, including firm time limits for environmental reviews, greater applicant involvement in the process, and more efficient reviews for recurring small projects we already know have minimal environmental impacts, will allow co-ops to build new generation and transmission infrastructure in a timely and cost-effective way.

The electric grid needs more transmission capacity to meet expected growth in the coming decades.¹⁰ While Associated and its six transmission cooperative-owners are making significant near- and long-term investments in its transmission system, the timeframe to add new lines capable of supporting reliability in an era of increasing intermittent energy will be measured in decades, not years. However, the costs of building out the grid must not be placed on the backs of communities, including marginalized rural communities, that will not receive commensurate benefits. Policymakers should ensure transmission projects and permitting proposals adhere to three key principles: they must not expand FERC authority over electric co-ops; they must allocate the costs of building new transmission or modifying existing facilities only to those who receive tangible and quantifiable benefits; and they must ultimately serve the national interest of maintaining the reliability and affordability of the electric grid.

Supply Chain

Electric utilities are facing unprecedented challenges procuring basic equipment needed to keep the lights on. Supply chain delays are already contributing to an unprecedented shortage of the basic

⁹ Executive Office of the President Council on Environmental Quality, EIS Timelines (2010-2018) (June 12, 2020), https://ceq.doe.gov/docs/nepa-practice/CEQ_EIS_Timeline_Report_2020-6-12.pdf. See also National Association of Environmental Professionals, 2021 Annual NEPA Report 8 (2022), https://naep.memberclicks.net/assets/annual-report/NEPA_Annual_Report_2021.pdf.

¹⁰ National Academies of Sciences, Engineering, and Medicine. 2021. *Accelerating Decarbonization of the U.S. Energy System*. Washington, DC: The National Academies Press. <https://doi.org/10.17226/25932>.



machinery and grid components essential to ensuring continued reliability of the electric system. For example, the recommissioning of Associated's Unionville Power Plant, a 44 MW fuel oil unit needed to support reliability, experienced significant delays when critical parts for its new control system were unavailable. When needs cannot be met, projects are delayed or cancelled. NERC in its 2022 Long-Term Reliability Assessment highlights that along with planning uncertainty, substantial supply chain processes must be addressed for future generation resources to materialize.

One of the most serious supply chain threats to electric reliability is the availability of electric transformers. Electric cooperatives are waiting a year, on average, to receive distribution transformers – a fivefold increase since 2021. Additionally, lead times for large power transformers have grown to more than three years. As a result, new projects are being deferred or canceled, and electric co-ops and other utilities are concerned about their ability to respond to major storms due to depleted stockpiles. NERC calls attention to this issue, noting that for this summer, “low inventories of replacement distribution transformers could slow restoration efforts following hurricanes and severe storms.”¹¹

Last year, the Electricity Subsector Coordinating Council, a partnership between the electric sector and the federal government, established a supply chain “Tiger Team” and made short and long-term recommendations based on their findings. In keeping with those findings, we urge Congress to:

- Utilize Defense Production Act authorities to finance a labor incentive program to hire and retain more workers and boost output at existing facilities;
- Establish a purchase guarantee by which the federal government can serve as a backstop or “purchaser of last resort” to give manufacturers confidence to invest in long-term capacity growth; and
- Urge DOE to reconsider a recent proposal to mandate new efficiency standards for distribution transformers, which is already hindering efforts to increase the number of transformers available. NERC has highlighted that “new efficiency standards for distribution transformers proposed by [DOE] could further exacerbate the transformer supply shortages” this summer.¹²

Availability of natural gas

The U.S. is increasingly reliant on natural gas for baseload power and as a backstop for intermittent generation sources. The ongoing robust capacity and resilience of the natural gas production and delivery system will be critical to maintain reliability for Associated's system. The availability of natural gas, however, has been challenged by several recent extreme weather events. During winter storm Uri, the natural gas delivery system was unable to deliver fuel to Associated's Holden Power Plant. As a result, the plant was required to use its back-up system, requiring the delivery of millions of gallons fuel oil to the plant for use during the height of the event. During winter storm Elliot, Associated's Dell Power Plant experienced periods where gas was unavailable due to pipeline compression issues.

Although NERC's assessment is that stored supplies of natural gas are at high levels for this summer, it emphasizes that “fuel supply and delivery infrastructure must be capable of meeting the ramp rates of

¹¹ North American Electric Reliability Corporation. *2023 Summer Reliability Assessment*. May 2023. https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_SRA_2023.pdf

¹² *Ibid.*



natural-gas-fired generators as they balance the system when solar generation output declines.”¹³ In particular, NERC notes that in the long-term, severe weather events and limited natural gas infrastructure in various regions of the country could pose a risk to natural gas fuel supplies.

Pipeline companies are also experiencing challenges on new projects that are being slowed by permitting, environmental and supply chain issues. We agree with NERC’s recommendations¹⁴ that there must be greater coordination and collaboration between regulators and industry to address the reliability needs of and risks associated with interdependent electricity and natural gas infrastructures as well as the need for additional pipeline infrastructure to ensure reliability.

Conclusion

The growing risk of rolling blackouts across the nation is unacceptable. Providing reliable, affordable, and responsible electricity remains the shared commitment of Associated and all electric cooperatives across the country. We look forward to working with this Committee and others in Congress as we work to fulfill that mission.

¹³ *Ibid.*

¹⁴ North American Electric Reliability Corporation. *2022 Long-Term Reliability Assessment*. December 2022. https://www.nerc.com/pa/RAPA/ra/Reliability%20Assessments%20DL/NERC_LTRA_2022.pdf

The CHAIRMAN. Let me thank all of you for your testimonies. We appreciate very much the input and your expertise.

We will start with the questions now, and I am going to ask one for all the witnesses.

From what we just heard, reliability should be the driving force, and the only way you know that is when you lose power and why it wasn't prevented. So with that being said, we have NERC, we have FERC, we have EPA. EPA seems to trump everything with policy if they are going a different direction, and it looks like there is not much input. Do you all believe or not believe it's necessary that NERC and FERC should have input as far as reliability when EPA is making these policy changes?

Mr. Tudor.

Mr. TUDOR. Absolutely.

The CHAIRMAN. Dr. Lott.

Dr. LOTT. I think within all these processes it is critical to keep what you highlighted in the beginning in mind—reliable and affordable electricity, and anything that affects the grid, we should understand the impacts of it.

The CHAIRMAN. But I am saying, if they are not listening—NERC and FERC are doing their job, but there's no teeth to it whatsoever. To give you an example of what we are talking about—we have been working on bills here directing the NERC to comment on EPA regulations, direct them to comment on your regulations. EPA must address NERC's comments before it issues a final rule, and then FERC can issue temporary waivers to regulations if needed for reliability. So somehow you have to have—reliability is going to be the first and foremost for people's lives, protect their lives, really, livelihoods and lives. And that is what we are asking, if something is needed that you all believe, seeing it from your standpoint, in legislation that might be helpful to give us more direction of reliability, not just changes that are desired.

Mr. ASTHANA. Yes, Senator Manchin, I can provide my perspective. I think, absolutely—I think actually Senator Barrasso is thinking through the SPUR—

The CHAIRMAN. Right.

Mr. ASTHANA. SPUR Act. And I think this concept of reliability impact statements to inform policy before it is made is a great idea. I think, actually, we can go further and I can talk about that later, but I think that is needed.

The CHAIRMAN. I think I know how you feel, Mr. Robb.

Mr. ROBB. Well, we do reflect the impact of EPA policy.

The CHAIRMAN. How frustrating is it to you being the head of NERC knowing that you are giving, basically, on the facts, you are not picking winners or losers. You are not getting involved in environmental climates and the fight that goes on, what side are you on, basically, just dealing with the facts of how you are supposed to deliver the power and no one pays attention.

Mr. ROBB. It's frustrating.

The CHAIRMAN. I would think so.

Okay, Mr. Asthana, how's PJM adjusting to the market rules to ensure that you have dispatchable power that is needed to run your reliable grid?

Mr. ASTHANA. Yes, great question, Senator Manchin. So we are taking a lot of actions right now. I think before I get into those actions, I just want to note that the markets have worked. They actually have delivered reliability. They have delivered the dispatchable generation we need for 20 years. And I think they will continue to work, but what is different is, there is this massive policy pressure. And I am not sure that the markets, or actually——

The CHAIRMAN. Explain that massive policy pressure. Pressure to what?

Mr. ASTHANA. There is——

The CHAIRMAN. Bring on more power, or just, I mean, here, bring on renewable? We are all for all-of-the-above.

Mr. ASTHANA. Yes——

The CHAIRMAN. Wind, solar, all of this.

Mr. ASTHANA. It's really pressure for generators that are dispatchable to retire, and the retirement dates are not tied to demonstration that the replacement capacity is here. And so, it's not——

The CHAIRMAN. Let me ask this question—if you shut down a coal-fired plant before it is timed out, and it can still produce power 24/7, you are shutting it down because of policy pressures. Does the ratepayer still pay since it has been based in for a longer period of time to run?

Mr. ASTHANA. It depends on the rate regime. So part of PJM is restructured, in which case the investors take that risk. In the fully regulated, integrated parts of the market, the ratepayers take that risk.

The CHAIRMAN. And——

Mr. ASTHANA. But so, we are doing a lot to tweak our markets and change our markets to make sure we are recognizing the attributes that we need for a reliable grid, whether it's resource accreditation, or how we run our auctions, or how we actually penalize people who don't perform.

The CHAIRMAN. Great.

Very quickly, I think, Mr. Tudor, you made a comment that you don't think that we can meet it in time as far as, you are saying, all of this in the queue, all this new energy coming on, waiting to get connected, correct? What happens if we do not build new transmission lines to carry this and bring it into the queue? Does it replace, basically, and if it's not, if we don't have the storage and we can't store it, and basically it has to be either used or lost, what does that do to reliability?

Mr. TUDOR. I believe there is a tipping point that is going to occur in 2028 because all the plants that are announced to close in 2028, most of these coal plants are tied to specific regulations in the EPA. So they are going to close. So you have between now and 2028 to come up with solutions, sir. Transmission is a solution. Keeping what we have past 2028, to maybe 2035, gives us a chance to actually see these technologies develop. The first SMR—small modular reactor—is scheduled to come on in 2029. That is the first one. And no one wants to be number one in new technologies.

So my concern is we have a gap period here that we have this push for all these new renewables, and we have this push to shut down plants that work, and there is nothing there in the middle

to save us, and I fear we are going to have blackouts. I am afraid we are going to see a significant number of lives lost.

The CHAIRMAN. Thank you.

Senator Barrasso.

Senator BARRASSO. Well, thanks so much, Mr. Chairman.

Mr. Tudor, to follow up, I want you to take a look at a chart that I have posted here. We have circled the area in green that is the area served by your cooperative and its affiliates, as you mentioned, Missouri, Iowa, Oklahoma.

[The chart referred to follows:]

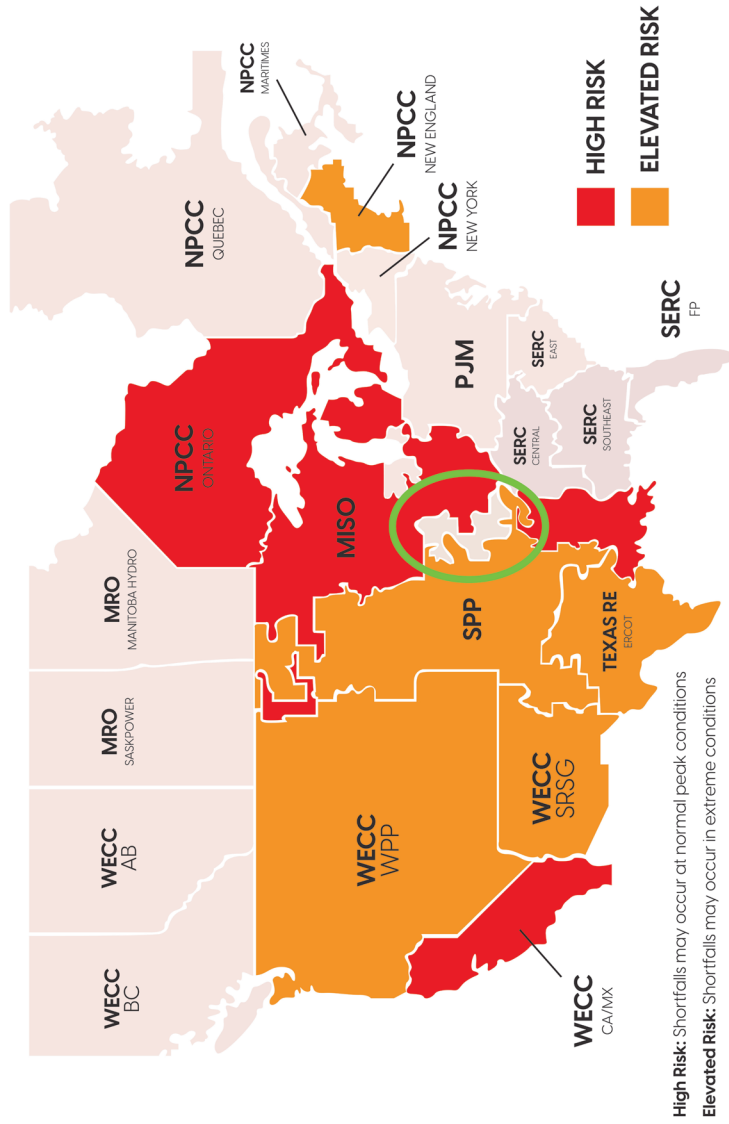


Figure 1: Risk Area Summary 2023–2027
Source: NERC 2022 Long-Term Reliability Assessment

Senator BARRASSO. So this chart is from NERC's 2022 Long-Term Reliability Assessment. It is entitled "Risk Area Summary from 2023 to 2027." So red is high risk. Orange represents elevated risk. The area that your cooperative serves appears as an oasis—surrounded by red and orange, except you are in a good spot. So why is your area in such a good spot? What are you doing right that your neighbors are not doing right?

And could you just turn this so the other members can see, Senator Cassidy, as well as Senator Murkowski—

Senator CASSIDY. Can you hold it up over Mike Lee's head? It's right in the way.

[Laughter.]

Senator BARRASSO. The oasis among—

Senator MURKOWSKI. And where is Alaska?

[Laughter.]

Mr. TUDOR. Now that's a good question.

Senator BARRASSO. It's where it belongs, above all the rest.

[Laughter.]

Mr. TUDOR. To answer your question, sir, we have not retired our fossil fuel plants, number one. Number two, we invest in transmission projects to serve our members to maintain affordable electricity to their homes. Our ability to also have 200 interconnects with SPP and MISO. We also have firm transmission to go across TVA to PJM. So we can access all three markets in those times when there are problems. Most of you know how storms go from the west, typically, to the east. And so, our system sits right in the middle of these markets. And what we are concerned about, frankly, is over the next four or five years, so much of this coal generation is going to get retired in the Midwest, that we believe that both MISO and SPP are going to become, more and more, less reliable. And we can't just open the breakers and keep them from affecting our system.

So what we are worried about is, we feel like we have done everything we can to protect our membership from a reliability standpoint, but those 200 interconnects are both a blessing and a curse. They are a blessing, you know, to get extra power when we need it, which is very seldom. They are a curse because we will have loop flows and, you know, a lot of people do not understand what that is, but electricity goes where it wants to. You can't make it go a certain direction. So our fear is we are going to become less and less reliable, not because of our own actions, but because of the actions of others.

Senator BARRASSO. So a few weeks ago, Mr. Tudor, this Committee held an oversight hearing. We had the FERC Commissioners here. The Chairman had made mention of it. During that hearing, Chairman Manchin asked each of the FERC Commissioners whether, quote, "it is possible to eliminate coal today or in the near future?" All four Commissioners agreed that we need coal to maintain grid reliability. Do you agree with the Commissioners?

Mr. TUDOR. Yes, sir, I agree. And I believe you would hear from both MISO and SPP, as PJM has stated, that yes, we need to maintain some baseload generation—coal, and natural gas—until we can get to a point where there is a new technology that can replace it.

Senator BARRASSO. And that is specifically for your own cooperative as well as across the nation?

Mr. TUDOR. It's the United States, sir.

Senator BARRASSO. Thanks.

Mr. Robb, your organization's 2023 Summer Reliability Assessment shows risks spreading to even more regions than the assessment from last year, and your 2022 Long-Term Reliability Assessment showed much of the country at higher elevated risk, worse this year. So as utilities and cooperatives face greater pressure to retire coal and nuclear and even natural gas power plants, the grid faces even greater risk, as indicated by your chart. Based on these trends, is the electric grid at greater risk of failure today than it was, say, 10 years ago, in 2013?

Mr. ROBB. Unquestionably.

Senator BARRASSO. So I won't ask you to predict what is going to happen, but if current trends continue, what would you project the state of the grid to be five years from now, in 2028?

Mr. ROBB. Well, since you have both showed our maps, if the trends continue as they are today, we are going to see more of the country in orange and increasing areas in red. So more elevated risk across the country, more red areas of high risk. And when we do our next reliability assessment, we will be baking in all these coal retirements that we are talking about today, and that is going to make almost the entire map orange.

Senator BARRASSO. Well, Mr. Chairman, I am out of time. Thank you. I will go a second round.

The CHAIRMAN. Thank you, Senator.

Now we will go to Senator Heinrich.

Senator HEINRICH. Thank you, Chairman.

Dr. Lott, a recent study commissioned by ERCOT, the Electric Reliability Council of Texas, that I have here, indicates that the reliability of conventional fossil fuel thermal electric generation was reduced in cold years, particularly cold winters, like the years we had in 2011 and 2021, by about 20 to 30 percent. So this is the thermal generation that we are all talking about, but in particularly cold winters, like 2011 and 2021, they saw a 20 to 30 percent decrease in reliability due to correlated outages that are caused by extreme weather events. In general, are we talking enough about the reliability of conventional gas and coal plants being overestimated in those windows, given the demonstrated risk from correlated outages?

Dr. LOTT. In general, we are not spending enough time looking at the trade-offs and risks across all the different technologies and how they pair together, and to a point that was made earlier, also the systems that are connected to them. You can have a natural gas plant, which will have its own risks, as one example. You also have to think about the entire fuel supply chain, so the pipelines, the storage, the wellheads.

Senator HEINRICH. Yes, the valves that get stuck.

Dr. LOTT. All of it.

Senator HEINRICH. Would it have been helpful during events like Winter Storm Uri if Texas could have actually imported bulk power from neighboring markets?

Dr. LOTT. The ability to import is one additional tool in the toolbox. In the middle of an extreme event, you want every tool available to you. So the fact that they had limited ability to do that meant that they had one less tool to work with.

Senator HEINRICH. Mr. Asthana, as of 2022, PJM had one of the largest interconnection backlogs in the nation for new generation and storage projects. I believe it was about 280 gigawatts, at least according to the Lawrence Berkeley National Lab report that I saw. As you and others have pointed out, this backlog and the inability to add new generation sources on the grid is a challenge for reliability and for our ability to transition to cleaner resources. I am curious, do you think that FERC's NOPR to address interconnection backlog issues is on the right track, and in addition, when you say interconnection reform, what specifically does that mean to you? What does that look like, in particular?

Mr. ASTHANA. Yes, great questions. I will take the second one first. The queues are full. And we need to get through them. There is no question about it. They are full because they are full of projects, some of which are going to go, and many of which are speculative. And we have to separate them and do our engineering work on the ones that are going to go. And so that is a lot of our reform that we have put in place right now, and it should get us through the queue in the next few years.

Now, in terms of the FERC NOPR, we were in——

Senator HEINRICH. So specifically, you are saying if you just separate—I mean, how do you separate those two buckets? Because sometimes people are, you know, what one person, what one developer calls speculation, another developer says no, we are putting that in the queue because we are betting that we can get a connection at that location.

Mr. ASTHANA. Yes.

Senator HEINRICH. How do you separate those two buckets of speculative, and things that from your point of view are ready to go?

Mr. ASTHANA. Our solution requires demonstration of site control. So you have to show that you have the land and control of the site.

Senator HEINRICH. Yes.

Mr. ASTHANA. And you have to be willing to put down financial deposits that are at risk to show that you are serious.

Senator HEINRICH. Great. That is helpful.

Mr. ASTHANA. And with regard to the FERC NOPR, in concept, we were supportive of it. We provided extensive comments. There were parts of it that we suggested needed tweaking, but I do think more proactive planning of the grid is going to speed up interconnection.

Senator HEINRICH. Mr. Robb, do you agree?

Mr. ROBB. I agree with that. The one thing that we have pushed on from our perspective with the FERC NOPR is to ensure that inverter-based resources are correctly modeled before they are——

Senator HEINRICH. Right.

Mr. ROBB. And that has been a big issue.

Senator HEINRICH. You have indicated that the rapid growth of inverter-based renewable energy on the grid poses challenges for

the bulk power system. However, I was looking at NERC's 2022 report, the Inverter-Based Resource Strategy, and it actually says, implemented correctly, inverter technology can provide significant benefits to the bulk power system. Is there a disconnect there?

Mr. ROBB. No, there is a big proviso in there of being integrated correctly, and the key issue here, the major issue with inverters is to make sure that they are able to ride through minor grid disturbances. We have seen a couple major events, most recently in West Texas, where a minor disturbance on the grid that would have cleared itself automatically caused a number of inverters to panic, if you will, and trip off the system. And since they all see that, we end up having very large outages. So in the most recent West Texas event, a minor disturbance that would have been cleared naturally resulted in 1,700 megawatts of inverters tripping off the system. That resulted in 800 megawatts of conventional generation tripping off the system. We lost two and a half gigawatts, which is two and a half nuclear units.

Senator HEINRICH. Right.

Mr. ROBB. And put ERCOT very, very close to having to shed load.

Senator HEINRICH. Thank you.

Thank you, Chairman.

The CHAIRMAN. Thank you, Senator.

Now we have Senator Lee.

Senator LEE. Thank you very much, Mr. Chairman, for organizing this hearing. Thanks to each of you for coming here to enlighten us.

You know, it has become very popular to talk about the negative impacts of using coal and natural gas, but we really should have a conversation about the extent to which we rely on them, and about the positive impacts of using them, and the fact that the American people benefit from them in ways that can't simply be overlooked and dismissed. The reality is that human beings are able to survive and thrive much more readily, much more comfortably, and much more affordably because of affordable and plentiful and reliable power, primarily coming from natural gas and from coal.

And so, the advantage that fossil fuel electric power generation provides isn't something that we can just ignore. It's something that makes it not only affordable, but also available on demand as baseload power on a consistent basis. We all benefit from that, from being able to walk into a room and turn on the light switch and know that the lights are going to come on and it will be affordable and reliable. Sadly, we are seeing an all-of-government-approach war on reliable power waged by unelected, unaccountable bureaucrats in the Biden Administration. It's just one of many examples. The Biden EPA has been on a crusade against coal-fired power plants, imposing crippling new regulations in what seems like every single week.

Mr. Robb, I would like to start with you.

NERC, the organization that you lead, is the reliability watchdog for the grid. Is that fair to say?

Mr. ROBB. It is a fair characterization.

Senator LEE. And I think most of us can agree that coal-fired power plants are being retired prematurely, which is especially alarming when you look at the realities on the ground, when you consider things like the fact that when replacement baseload power supply has not been brought online, we need to be worried about this. Tell me why this trend should be troubling to us, or is it troubling to you?

Mr. ROBB. It is highly troubling because we are retiring these plants before their attributes are being fully replaced. And their attributes are more than just the energy that they produce. One of the important things, it is a little esoteric, but one of the important things that these plants provide is the ability for the grid to maintain voltage and maintain frequency and to resist disturbances. Other resources can't do that nearly as well as large, spinning mass generation. And that is why the loss of coal plants and natural gas plants and nuclear plants is so concerning from a grid reliability perspective.

Senator LEE. Okay, so it goes beyond cost. It is about reliability, and without reliability, we lose some significant benefits. Now, requests for future generation published by the large regional transmission organizations, or RTOs, show that the vast majority of projected future generation additions are going to come from wind and from solar. For example, within MISO, one of the largest RTOs, solar and wind comprise 64 percent of new generator requests, while natural gas comprises only three percent of those requests. Given the retirement of dispatchable power, will this ratio of new wind and solar projects on the one hand, to natural gas-fired projects on the other hand, be sufficient to meet the need, the demand for reliable power in the coming decades?

Mr. ROBB. It will be highly problematic without reinforcing the natural gas system, which is very, very important for integrating renewables and/or the eventual development and deployment of long-duration energy storage, which, as yet, does not exist at scale.

Senator LEE. Right.

Mr. Tudor, you lead a large electric cooperative. I have been very interested in your work and I am interested in your thoughts on why coal-powered plants are being forced to retire as they are, and why investment in new natural gas plants is seeming to be stifled. Tell me, do regulations like the EPA's Good Neighbor Plan, do they make blackouts more likely or less likely?

Mr. TUDOR. More likely. Any premature retirement of something that works without having something that doesn't work to replace it seems dangerous to me and illogical. So yes, there has been a continuous push to retire fossil fuel plants, mainly coal, and now move on to natural gas plants. And what it has done is, it has—

Senator LEE. Move on to them, meaning?

Mr. TUDOR. Retire them.

Senator LEE. To retire them?

Mr. TUDOR. Yes, sir. Or not even build any, and you know, people are afraid to try and build something that is fossil when the EPA regs continue to come out that are negative to an investment of any kind in fossil fuels. So if you are sitting here going, am I going to build a windmill or am I going to build a gas plant? I am going to build a windmill. Why? Because you can, as it will be very

difficult for that three percent that we are talking about here of new natural gas plants to get permitted, get in the queue, and get connected to the grid and actually get built and completed. And it takes five or six years now to build a brand-new natural gas plant, where it used to take two to three.

Senator LEE. In the meantime, they are not replacing that with nuclear power, traditional or small modular nuclear. They are not replacing that—

Mr. TUDOR. They can't yet—

Senator LEE. With geothermal or hydroelectric.

Mr. TUDOR. They can't yet because the technology is not there yet. I mean, there is a big difference between *capacity*, which is the ability to deliver energy, and *energy*. So if you take a wind product, which I am not against wind, but wind, in general, gets about 15 percent capacity credit in the RTOs, where a coal plant gets around 80 percent capacity in an RTO. What that means is, the coal plant produces and runs 80 percent of the time and the wind farm runs 15 percent of the time. When it's windy, the wind produces a lot of energy, which is a good thing. When it's not, you virtually have nothing, and you have to rely, as Mr. Robb is saying, you have to rely on something that is baseload to maintain the integrity of the service, basically, to our consumers.

Senator LEE. Thank you.

Thank you, Mr. Chairman.

The CHAIRMAN. Thank you, Senator.

And now, we have Senator King.

Senator KING. Thank you, Mr. Chairman.

As I have been listening to this hearing, it occurs to me there is an irony and a paradox embedded in the hearing. We have heard the word premature about a hundred times. The question is, and I will quote the testimony of Dr. Lott: "The American Society of Civil Engineers identify severe weather as the predominant cause of customer outage." Right? It's in your testimony. We are in a race with climate change. And we are talking about outages that are caused predominantly by severe weather, which is a result of climate change. So the question is—premature? Actually, we should have been making this transition years ago, and we are trying to make it in a hurry because we are in a crisis situation.

For the last million years, CO₂ in the atmosphere averaged about 260 to 270 parts per million. Starting at about 1850, that started to rise steadily. Today, it is at 424 parts per million. I remember ten years ago, when I entered this body, it was under 400, and everybody said 400 is a tipping point. We are at 424 today. That is a 60 percent rise in about 150 years. And by the way, the last time we were at over 400 parts per million was three million years ago and the ocean was 60 feet higher. So the question is—and I understand that it seems to me the heart of this hearing is timing—and is it—what is the time period? Is it five years, or ten years?

Mr. Robb, I understand the testimony, and basically what you are saying is that we are trying to transition too fast. My question on this—an honest question—is, what is the right time period that we should be aiming at?

Mr. ROBB. It's a terrific question and it's a very tough policy problem and I have sympathy—

Senator KING. Can the record show that terrific question quote, please?

[Laughter.]

Mr. ROBB. I believe, and I think most people studying the energy systems say you need to keep balance between affordability, reliability, and climate. And if one gets out of whack then bad things start to happen. And I think your question, at its roots, is how much do you value having 24/7 energy available to support the way of life we have all become accustomed to?

Senator KING. And how do you avoid the crisis that will overwhelm any electric system?

Mr. ROBB. And that is the question of balance that policymakers need to figure out and pursue.

Senator KING. So can you give me a year? Is it five years? Is it ten years? Should we—

Mr. ROBB. I think it depends—

Senator KING [continuing]. Slow the retirement of coal plants which are definitely—

Mr. ROBB. Yes, Senator, I think it depends on what you believe about our ability to create batteries or other forms of storage that can create synthetic dispatchability from intermittent resources like wind and solar.

Senator KING. It's not synthetic dispatchability. It is dispatchability. You have batteries plus renewables. That is a base-load plant.

Mr. ROBB. And the question is, at what time do we have the duration that we need, because right now, a four-hour lithium-ion battery is incredibly helpful to the grid. It does not solve the wind drought problem.

Senator KING. I completely understand that. So the question is, how fast can we develop the battery or the storage technology, whatever it is, whether it is pumped storage or something else, versus the contribution to the severe weather events which are also—we are talking about this hearing as if the only risk is the lack of capacity, when in reality, the risk is severe weather events. So we have got to try to beat—

Mr. ROBB. And the issue is, they are correlated, right? And we need to recognize that and find the right balance between them, but I think people need to understand that the scale of this industry is enormous. So last year we put 20 gigawatts of solar onto the system. That is the most we have ever put on in a single year.

Senator KING. That is only going to accelerate.

Mr. ROBB. And that is only about two percent of the capacity of the United States. So with everything that we have done to speed the development of renewables and so forth, with the static grid, we are on a 50- to 75-year trajectory to replace it. And the grid is not static because we are also trying to electrify transportation. That is a very smart thing to do. Space heating—

Senator KING. I am running out of time, but for the record, I would like you to give me a number of years. How long should we delay the retirement of the fossil fuel plants, bearing in mind the acceleration of the climate race?

Mr. ROBB. I am going to disappoint you, Senator. I can't give you a year, but we should not retire them until they are replaced.

Senator KING. Well, we have got to make decisions here as to—this hearing is about delaying the retirement. I want to know how long and how that relates to the rest of the risk.

The other point I want to make, Mr. Chairman, we had a very informative hearing just before the break about small modular reactors, and this country is falling behind in that technology. There is a danger of us losing whatever advantage we might have. I think we are going to need a CHIPS and Science Act II with regard to the development of small modular reactors to accelerate that development here in this country because that will answer many of the issues that we are discussing today, both climate and reliability.

Thank you, Mr. Chairman.

And thank you for calling this important hearing.

The CHAIRMAN. Very important. Thank you.

Senator Cassidy.

Senator CASSIDY. Well, I think if there is a lesson here, I mean, if there is a mental lesson, it is that the regulatory state is often conflicted and the regulatory state has created an environment with goals that are mutually incompatible. Mr. Tudor, you mentioned how the regulations are effectively forcing the retirement of coal-fired plants and inhibiting the development of natural gas. We have a limitation from the bureaucratic state of permitting for power lines, which would allow electrons to go from one place to the other. My Chairman mentioned in his opening statements how EPA is not approving carbon storage projects. And yet, theoretically, we are trying to decrease the carbon footprint of all these projects. You know, of course, the line from Pogo always comes to mind in this situation—"we have met the enemy and he is us." Except this time, to be more specific, it is the bureaucratic state.

So I will say on a bipartisan basis, I think that a regulatory reform bill would actually be incredibly helpful. That could actually help develop goals that are mutually held by both sides if we want to achieve anything, because right now, Mr. Tudor, you are suggesting we are headed for a train wreck. Now, if you noticed on that thing that Senator Lee's head was blocking earlier, I was trying to get around his ears to see—

The CHAIRMAN. We have been trying that for a long time.

[Laughter.]

Senator CASSIDY. Louisiana was just part of the MISO considered at high risk. We do not have that much dispatchable renewable, but we obviously have a lot of storms coming off the Gulf and I assume that is why we were considered at high risk.

In the Bipartisan Infrastructure bill, Mr. Robb, there was \$3 billion for distributed energy, \$3 billion to harden the grid, and \$3 billion to tie the two together. Now, what do you see as the potential for this distributed energy build-out to give resiliency to these weather events that Senator King was speaking of?

Mr. ROBB. I think the movement to push more generation closer to load is a good one, right? And I think distributed generation, as you are referring to, is a positive trend. The challenge with it is that most of that distributed energy is coming on in the form of inverters—largely photovoltaic, some wind, and eventually we are going to see more and more batteries. We need to make sure that those inverters play nicely with the rest of the—

Senator CASSIDY. Now, I was told by somebody who is very much into this, so you always have to kind of understand, you hear from different sources, that if you took a microgrid, connect it to a battery, that would give you four hours of power, which may be enough to get you back up. The thought came when you mentioned how in West Texas, the inverter flipped off, but if it was storing into the battery then putting it right back on. Would that not have dealt with the issue?

Mr. ROBB. The combination of inverter resources and batteries is a very powerful one, but you need to be cognizant of the scale and duration of protection that you are getting. Four hours is four hours, which is terrific if you have a three-and-a-half-hour event. If you have a two-week outage associated with a major hurricane, if you have six weeks of cloud cover that you can't generate from, you need longer duration storage than four hours.

Senator CASSIDY. So it's part of the solution, but it's not *the* solution?

Mr. ROBB. It's definitely part of the solution, but other things need to happen around it.

Senator CASSIDY. Let me just ask you, do you agree with Mr. Tudor that the EPA's regulations are forcing the early retirement of assets, and that we, in no way under the current regulatory regime, have any possibility of replacing it with suitable renewables and transmission to make up for it?

Mr. ROBB. Not in the timeframe that we are looking at, no.

Senator CASSIDY. So you agree with his testimony in the main?

Mr. ROBB. I do.

Senator CASSIDY. And Mr. Asthana, do you agree?

Mr. ASTHANA. I do agree we need to hang on to resources that we have today that work until their replacement is here.

Senator CASSIDY. And would you also agree that the regulatory state is basically making that impossible? You are a regulated industry, so you may be a little hesitant, but you can just surreptitiously nod your head yes.

[Laughter.]

Mr. ASTHANA. Well, I was trying to give you a thoughtful answer. I have said the policy pressure is what is pushing most of this generation off. So that is true. I was really hesitating because the most recent EPA rule is a proposal, and so I am not sure where it will end up, but if it ends up the way it is, it will continue to push this generation off the grid.

Senator CASSIDY. I think Mr. Tudor's point, that even their proposal ends up guiding bond markets—James Carville said he once wanted to come back as a bond market, because everybody listened to the bond market. So who is going to float a bond for fossil? I think that was Mr. Tudor's point.

And Dr. Lott, would you agree with all that?

Dr. LOTT. I think the system is not set up right now to support, at the speed we need, the diverse mix of technologies we need. If you want a reliable and affordable grid in any future scenario, you want a mix of things. You want variable renewables like wind and solar. They are very cheap when they are around. We want to complement it with energy storage, both batteries for these short periods of time, and the long duration we are establishing. We also

want firm dispatchable power. And I say that as a group of technologies. This could be geothermal, hydro—

Senator CASSIDY. I accept that, but it also means that we are going to have to have regulatory reform if we hope to achieve that. Would you agree with that, in the time required?

Dr. LOTT. We need processes that can provide transparency and speediness so that we can build things, yes.

Senator CASSIDY. And do we have that now?

Dr. LOTT. Our processes are not set up to do the number of things we are trying to do.

Senator CASSIDY. I will just finish by saying that should be the challenge of this Committee, to come up with that regulatory reform bill on a bipartisan basis.

I yield.

The CHAIRMAN. Thank you, Senator.

Now we have Senator Hickenlooper, from the great State of Colorado.

Senator HICKENLOOPER. Thank you, Mr. Chair, and thanks to all of you for your work and for being here. I think this has been very useful. I did want to point out Walt Kelly's great quote—that was my father's favorite cartoon, Pogo—but the reason that is so famous is, in 1970, he put that on an environmental poster and he was really talking about the causes of pollution and environmental challenges that we have created. He also—what is the other one we had here? “Having lost sight of our objectives, we redoubled our efforts,” which is something that this Committee has to be very careful of. Also, he said that “we are confronted with insurmountable opportunities.” I could go down the long list.

Anyway, that is neither here nor there.

Mr. Asthana, I saw in your testimony that PJM is over a quarter of a million megawatts. That has been brought up a couple different times, as we discuss. The PJM's recent analysis identified several concerning trends that could result in a capacity shortfall, as you recognize. You also consider different scenarios regarding how quickly you could bring on new generation. Can you talk a little bit about the “high new entry” scenario in which you are able to get a lot of generation out of interconnection queues and onto the grid? How does that impact the risk of blackouts and future interruptions?

Mr. ASTHANA. Yes, thank you for that question—great question.

So we have said we see 40,000 megawatts at risk of retiring by 2030. To replace it, we need 100,000 megawatts of the intermittent variation. We have 250,000 in the queue, so it's doable, right? Our interconnection reform will move that generation through the queue in time to get built. The problem is, the completion rates of those projects are really low. So we are going to need to get 50 to 60 percent completion rates when we are seeing five to ten percent because of issues like supply chain constraints, permitting, and the like. So it's doable, but I would not want to bet the farm that it will be done given the current trends. I think we need to push to get it done, but I think we need to not burn the boat in terms of the generation that we have in the meanwhile.

Senator HICKENLOOPER. All right, thank you.

And as Senator King pointed out, and you have all pointed out that the pressure that is coming to make these changes more rapidly really is coming from the public. I mean, the EPA, in many regards, is feeling that pressure, which is the occurrence of extreme weather. I have my master's—now it's almost 50 years' old—in earth and environmental science, and you go back, and back then we called it the greenhouse effect, but as early as the mid to late 1980s, we began predicting extreme weather was going to be a consequence of climate change as we saw it. When I first became Mayor of Denver in 2003, we had some of the worst wildfires we'd ever had. They have only gotten worse, continuously, in a cycle.

The question I have for each of you, if we are going to do this properly and measure, as Senator King was describing, how do we balance reliability with the urgency to address climate change before the extreme weather accelerates to a point where we really can't deal with it, which is not impossible to imagine. Do you think a price on carbon helps us assess—increase the system where we can assess these competing urgencies that I think we are all faced with right now?

Why don't we start with you, Mr. Tudor, and we can go right down the list.

Mr. TUDOR. Well, selfishly, I don't want to pay any more taxes.

Senator HICKENLOOPER. Well, if the money was all given back as a dividend.

Mr. TUDOR. Sure, I understand.

You know, in the past, tradable markets have had a positive effect on the reduction of emissions.

Senator HICKENLOOPER. Great. They have.

Mr. TUDOR. Yes, sir.

Senator HICKENLOOPER. Dr. Lott.

Dr. LOTT. So one of my colleagues at the Center on Global Energy Policy, Dr. Noah Coffin, works on this quite a bit. Putting a price on these things, as you say, has succeeded in the past when it comes to addressing things like acid rain, and it is one tool that can be deployed.

Senator HICKENLOOPER. Yes, and I do not underestimate the complexity of getting to doing this in a way that would be perceived as fair and just.

Mr. Asthana.

Mr. ASTHANA. Yes, I do think a price on carbon can get us to a more efficient solution to carbon mitigation.

Senator HICKENLOOPER. Great.

Mr. ROBB. As NERC, I don't think we have a point of view on that—

[Laughter.]

Senator HICKENLOOPER. Yes, I would have to come up with a more political problem, probably than it needs to be or should be, and it certainly was generated by Republicans and Democrats, but I keep circling back because so many people in Congress have given up on it, and it is the one sure way to find out a solution whereby government gets their finger off the scale, and where we let some of these systems that we all recognize are complex but important that allow the system to generate its own priorities.

Mr. Tudor.

Mr. TUDOR. I would prefer that to the latest EPA rule on 111(b) and (d) because what that does is exactly what you are saying, is it forces things into unintended consequences. I would much rather have a market to cause that versus unintended consequences of set rules that will require retirements.

Senator HICKENLOOPER. I understand that, and I appreciate what Dr. Lott said in terms of as we look at revisiting the processes that we use to look at that type of rulemaking. How do we make sure that we can maintain the transparency? We can accelerate the time, but we have got to make sure we protect the role of the public in having an opportunity to discuss their own future as well.

I yield back to the Ranking Member.

Senator BARRASSO [presiding]. Thank you, Senator Hickenlooper. Senator Hyde-Smith.

Senator HYDE-SMITH. Thank you, Senator Barrasso, and thank you all for being here today. This has been so helpful, and obviously we have a lot of challenges in front of us that are very, very critical.

Mr. Tudor, I am going to direct my question to you. The strains on the nation's electric grid, to the electric sector, continue to be plagued by the things you talked about—the supply chain issues, the labor shortages, the natural disasters, the reliance on foreign countries for equipment and so on. We are also seeing that the challenges facing our grid infrastructure are only heightened by the aggressive green agenda being pursued by the Biden Administration. So from your perspective, can you just talk about the consequences that the American people will see if these issues are left unaddressed?

Mr. TUDOR. I apologize, are you asking me?

Senator HYDE-SMITH. Yes.

Mr. TUDOR. Okay. Very good question. Difficult to answer. I have to revert back to probably the largest issues. Supply chain challenges are worse than they have ever been. Minerals to actually create renewable projects are 70 to 80 percent managed and controlled by China. You have to get—you have to construct things. So when we talk about implementation, the first thing we have to do is we have to invent and develop, and then ultimately deploy whatever resource we are talking about, whether it's wind, solar, or batteries. And I agree with Dr. Lott, we just don't—it's just not prime time yet. We are not ready. And we have had some unique things happen to have caused this to slow down. A big one being COVID, which created the supply chain challenges, a strong economy led to that, and this growth spurt.

And so, I think that we need to answer Senator King's question. I think we need until at least 2040 to maintain fossil fuel plants and make a smooth transition to a cleaner United States. That doesn't fix the world, it will just fix the United States, because China is going to continue to build coal plants.

Did that help, did that answer your question?

Senator HYDE-SMITH. Yes.

Mr. TUDOR. Thank you.

Senator HYDE-SMITH. And also to you, you know, with the Winter Storm Elliot strike that we had in the Southeast, you know,

there were certainly reliability problems and concerns, including the rolling blackouts. And it seemed that the region recovered pretty quickly, but the customers did not see the extreme economic impact like they did in Texas or that they might see in a market like New England that lacks firm gas. So do you attribute this, in part, maybe, to the market structure in the Southeast or specifically the vertically integrated bilateral market?

Mr. TUDOR. Storms are unpredictable, and we have actually looked back at our region and looked at weather trends. And when was the coldest day in Missouri, Oklahoma, and Iowa? It was actually in 1989, not in December 2022. What happened in the Southeast is somewhat unique, as well as Texas, because they are not used to these storms dipping down as deep and as cold. So what we experienced in Elliot was, effectively, 20 and 30 degrees below zero with wind chills and wind up to 50 miles an hour. Very unique storm. It has happened before, but the southeast effectively, I think, got caught by the same thing all of us got caught by, and that is bad weather forecasting. I think most utilities in the United States during storm Elliot missed their load forecast. And when everybody misses their load forecast—Jim knows what that means—you are short everywhere of generation. And if you don't have that generation on and operating before the storm, it's very difficult to get that generation to come on during a storm.

So from a market construct standpoint, I continue to advocate that we allow the RTOs to actually bring on baseload generation in front of a storm and curtail other forms of energy for that window of time where they need to get the baseload generation up and running in advance of a storm.

Senator HYDE-SMITH. Thank you.

And I have another question, but I will submit it. Thank you.

The CHAIRMAN [presiding]. Thank you, Senator.

And now we have Senator Cortez Masto.

Senator CORTEZ MASTO. Thank you, Mr. Chair, and I agree with my colleagues. This has been a really informative discussion.

Let me follow up because this is the question I was going to ask you, Mr. Tudor, was what is the appropriate time frame? And you said 2040. Why 2040?

Mr. TUDOR. First of all, I do not think hydrogen or carbon capture will be ready any time soon. I think our best opportunity for having a real resource that can replace fossil fuel plants is small modular reactors, which is nuclear. The problem there is the permitting process, and the cost that these organizations have to spend to get through that permitting process is enormous, and ultimately, that results in a cost of a small modular nuclear reactor close to ten times more expensive than a brand-new gas-fired plant. Over time, I think those costs will come down, but they need the time to develop that product—develop it, deploy it, test it, so it can be financeable. Banks are not going to loan money on something that they don't know whether it works or not, especially in advance, when your cost curve is so high and over so many years.

The first SMR scheduled to come online is in 2029 with a company called NuScale. We have signed a letter of intent with NuScale, specifically, as well as GE Hitachi to track this technology

and consider it, but we do not see it happening until 2035, and we do not even know if it works yet.

Senator CORTEZ MASTO. So let me ask you this. And it goes back to what Senator King was saying, is we knew about extreme weather impacting and making this change in directing us to do something years ago. So if the Administration does not put out some sort of incentive or goal marker or something out there, how can we ensure the industry and people—it's not just the Federal Government, right? The regulation comes at the state level, public utility commissions, local regulation, we all know that. How do we ensure, in the industry, that everybody is going to work toward that goal?

And so, I guess this is a question for Dr. Lott because you touch on this in your testimony, and I appreciate that, which is this idea that there is a role at the federal level. The U.S. regulatory framework for the electricity sector is overseen by state legislatures and public utility or service commissions, but you identify that the Federal Government has a role. And then you list a number of things. One of the things you talk about is that Congress could consider strengthening requirements for risk assessment and mitigation planning and power sector planning processes. Can you discuss that? And would that address what we are trying to achieve here, without putting a time—we need an off-ramp of some sort and for everybody to be a part of this—would that help pull in this conversation of what we need to be thinking about?

Dr. LOTT. Thank you for the question. It's a great one. When we talk about the integration of how we plan our energy systems, what I am highlighting in my testimony is that we have tools available today. They exist largely within our national labs, specifically Argonne National Lab. I will give an example in a second, where we can do energy systems planning and we use those models in conjunction with climate models that capture these changes that are already happening, that are already in progress today in a way that allows us to design a system that will be reliable, resilient, and affordable moving forward.

Right now, those models don't talk to each other. The specific example I was alluding to is a partnership between the New York Power Authority and Argonne National Lab, to actually do this kind of risk assessment. We have seen this done outside of the energy sector for the telecommunications sector, Florida, AT&T. How should we build out our network of wires there to keep coms up? And we can do that now for the energy system, so we aren't—not seeing risks that we already are facing today and therefore unable to invest——

Senator CORTEZ MASTO. But not all power authorities are doing this.

Dr. LOTT. No.

Senator CORTEZ MASTO. Not all power authorities are partnering with labs to do this risk modeling, correct?

Dr. LOTT. And there is a tremendous opportunity to make it so that those risks have to be included and have to be considered.

Senator CORTEZ MASTO. And there is a role for Congress to play to——

Dr. LOTT. Absolutely.

Senator CORTEZ MASTO [continuing]. Incentivize somehow or——

Dr. LOTT. Yes.

Senator CORTEZ MASTO [continuing]. Mandate that type of modeling being done?

Dr. LOTT. Because the risks are happening. We have the science and modeling and technology to assess it. So there is an opportunity for Congress to act to make sure that we are assessing that risk.

Senator CORTEZ MASTO. Okay. That is helpful.

Yes, go ahead.

Mr. ASTHANA. Senator Cortez Masto, I wanted to answer part of your question around timing as well. More than half of our queue is solar. Solar works. It is here today. We need to accelerate it. I mean, I do not think it's a binary thing where we will get to a date and we will be ready. I think we are going to transition. The transition is happening now. I think we need to make the new generation come faster. It's just a question of the existing generation that firms the grid. I think we need it. It will probably run less as the new generation comes in because the new generation has a zero marginal cost. So we will dispatch it first, but when it dries up, when we do not have sun, we do need the backup. So that is the issue. I do not think we should think of it as there is a date and then we will be ready. I think it's happening now.

Senator CORTEZ MASTO. Mr. Robb, do you feel the same way?

Mr. ROBB. I agree with that. I think keeping the foot on the gas and the deployment of renewable generation, deployment of batteries, development of new technologies, such as small modular reactors, long-duration storage, all that needs to be pursued at an extraordinary pace. We just need to keep the other stuff around because we need to have that "in case of emergency, break glass" capacity we can rely on.

Senator CORTEZ MASTO. Thank you.

Excuse me, Mr. Chairman. Mr. Tudor has one response to that, is that all right? I know my time is up.

The CHAIRMAN. Let it go.

Senator CORTEZ MASTO. Okay.

Mr. Tudor.

Mr. TUDOR. I think the IRA funding will actually be the incentive that is needed to continue this path for the development of renewables. I don't think you need anything else. I think it's going to cause it.

Senator CORTEZ MASTO. Thank you.

Thank you, Mr. Chairman.

The CHAIRMAN. Thank you, Senator.

Now we have Senator Hoeven.

Senator HOEVEN. Thank you, Mr. Chairman.

The CHAIRMAN. We are so blessed. We are so blessed with your arrival.

Senator HOEVEN. Well, I wanted to be here for you.

The CHAIRMAN. I know.

Senator HOEVEN. Okay.

So Mr. Robb, on May 4, FERC Commissioner Mark Christie testified before this Committee that the United States is headed for a reliability crisis. Commissioner Danly also emphasized that con-

cern in his testimony before this Committee as well. Do you agree with Commissioners Christie and Danly?

Mr. ROBB. I do.

Senator HOEVEN. Mr. Asthana, do you agree as well?

Mr. ASTHANA. I did not hear the quote, sir.

Senator HOEVEN. That we are headed for—both Christie and Danly have said that the United States is heading for a reliability crisis.

Mr. ASTHANA. I do think there is an increasing risk of that.

Senator HOEVEN. Mr. Tudor, would you agree with that?

Mr. TUDOR. Yes, sir, I do, and sometimes people forget that electricity is our way of life, and without electricity, we do not have water.

Senator HOEVEN. Good point.

Dr. Lott, do you agree with that?

Dr. LOTT. I agree that we are not making the investments we need to maintain a reliable system.

Senator HOEVEN. Mr. Robb, Mr. Asthana, and Mr. Tudor, in each of your written testimonies, you note significant concerns over the retirement of on-demand, dispatchable generation. Now, in my State of North Dakota, we have a 700-year supply of coal, just in my state, and we are leading the nation forward in carbon capture and storage technology. We are already doing it at a plant at Dakota Gasification Company that converts lignite coal to natural gas and also to fertilizer and produces other important elements as well, like krypton and xenon and so forth. Huge plant. Half its CO₂ will go for tertiary oil recovery—and already is—and the other half will be carbon capture. We have another plant that is investor-owned that is advancing with carbon capture and we have another one that is owned by a cooperative that is advancing with carbon capture.

Doesn't it make sense for us to do everything we can to help deploy those carbon capture technologies to keep that baseload on the grid for reliability when we have done that with SO_x, we've done that with NO_x, we've done that with mercury. And now we are doing it with CO₂. So rather than just coming out and saying, well, we can't have this kind of fuel or we can't have that kind of fuel or we have to retire this baseload and we can only have this, wouldn't it make sense to continue to advance the technology, not only because it will address the situation here in this country, but because the rest of the world will adopt it as well? Isn't that a better solution than just shutting down plants?

Mr. ROBB. I think investments that enable the continued operation of coal plants or natural gas plants would be an extraordinarily valuable technology for us to have and deploy.

Senator HOEVEN. Right.

And isn't it myopic if we just sit here and say, well, we are going to shut down our plants while China continues to build more and more and more? And there are a lot of other countries in the world that have an impact on the global climate, wouldn't you say?

Mr. ROBB. I would agree that it's the same air.

Senator HOEVEN. Okay.

Mr. Asthana, what is your thought on that question?

Mr. ASTHANA. Yes, I think carbon capture sequestration is a critical technology because our fossil reserves are a huge national security advantage for us. And I will say this, I think the most recent EPA proposed rule is trying to actually promote carbon capture and sequestration, but it is on a date certain, and it is not clear to me that the technology will be ready on that date, but I do think we need to keep pushing.

Senator HOEVEN. Mr. Tudor, what are your thoughts, and there's a difference between talking about it and making sure that you help people do it, right? You might want to add on that component as well.

Mr. TUDOR. Yes, sir, we—

Senator HOEVEN. In other words, if you're putting regulations in place all the time that prevent somebody from doing it, and then you're talking about it like you're actually trying to pretend to help them, that is not necessarily constructive to solving the problem, is it?

Mr. TUDOR. No, sir. I agree that we should spend incremental time and energy and money toward development of carbon capture, including allowing some other states, allowing us to actually inject the carbon in those states. You are one of the few in the country that allows that. So if a power plant is in Arkansas, they need to be able to inject the carbon in Arkansas. Otherwise, it is really expensive to build pipelines to get it to North Dakota.

Senator HOEVEN. Right, but you can't profess that you want to help them capture carbon and then pass regulations that prevent them from doing it, because it's unrealistic and defeat through delay, right? That would be kind of like talking through your hat, wouldn't it?

Mr. TUDOR. Yes, sir.

Senator HOEVEN. Okay, thank you very much.

Thank you, Mr. Chair.

The CHAIRMAN. Thank you, Senator.

And now we have Senator Murkowski.

Senator MURKOWSKI. Thank you, Mr. Chairman.

I really appreciate the conversation here today. This is probably as important as anything this Committee can possibly take up, is what this transition looks like because we are in this time of transition and it is about timing. I don't think it really is fair to assign a date when you are talking about a transition. You can have some benchmarks along the way. You can have some guideposts that get you there. I like Senator Cassidy's idea about this Committee looking to some level of regulatory reform, because it's through some consistency with regulation that you will send that signal to the markets, to the investors, that this is the direction that we are headed. And when you have got investment following, it's amazing what can happen in this country right now. But timing is just so hard. And I so get the fact that we are at this very, very, very awkward teenage pimply stage where we need to ramp-up and look toward the new future here, but we can't shed too quickly what we have relied on in the past.

But the problem is, we can put in place incentives. We can put in place some regulatory support to build us out going forward. But it's really hard to find the money to keep the doors open for aging

technology that needs to be maintained that nobody is interested in anymore. And yes, it's keeping the lights on, but it still costs money. And to the point that Senator Cassidy made about regulatory reform, it's not only hard to find the resources to keep the older stuff alive, but we now put in place newer regulations imposed on that that could make the cost of that even more extraordinary. So it's just a hard, hard transition that we are in.

We really haven't talked about affordability. And that is such a key part of it because you can talk about reliability all you want, but if you can't afford it, let me tell you, people in my state say that is not very reliable. And we see it all the time. We have had great success recently in building out water and sanitation systems in small villages, but by the time we get them operational, the systems are so expensive, people cannot afford to hook up. When the cost of power is so high in communities where it's cold and dark in the wintertime, and you can't afford it, you turn to what you have, which is burning wood, and sometimes it's green wood, and you are dealing with particulate and emissions, and that is really complicating this change. If it's all about climate, we are not making people healthier, and it's because of the affordability piece of it.

And Dr. Lott, I noticed that in your comments with response to just about everybody here, you say it needs to be reliability, but also affordability. You have focused on it, which I appreciate, and I do not think that we can lose sight of that. It's interesting to note that just a couple days ago, the U.S. Energy Information Administration (EIA) reported that energy insecure households were billed more for energy than other households. And so I look at that and I am concerned that as we are talking about reliability and what that means and what this means in terms of transition and timing, that the affordability piece of it is going to be the expendable piece because we have to keep the lights on. Well, you will be able to keep the lights on for those who can afford it. You will be able to keep the air conditioning on for those who can afford it, the heat on for those who can afford it. And what do we do about the most energy insecure?

That is an open-ended question. You have 45 seconds, Dr. Lott.

Dr. LOTT. Thank you for the 45 seconds.

Today, the conservative numbers are that one in three Americans is already energy insecure. They pay a huge amount of their income for their energy bills or they simply do not turn on the heater in the winter or the air conditioner in the summer because they know they can't afford it if they do that and they would risk losing their homes.

So when we talk about this affordability question, this is why I tried to highlight strongly in my testimony two things. One, that any types of policies and regulations need to not just think about power plants, but all the supply technologies that go into them, the grid and also the demand side, to the point that you made around, I am in a small home, I am low income, it is probably less energy efficient than someone who is in a twice-the-size home, and so I am paying more for my energy bills. And so, when we think about managing demand, it is not just about folks who can reduce their load during a winter storm event, it is also about being more effi-

cient in the first place and making sure that fundamentally people are staying safe and healthy in their homes.

And so, the other point that I highlight in here, the second point, is around having a diverse set of technologies that have different types of characteristics. The information indicates that if we go to a net-zero future all the way by mid-century, in that scenario, we still need the same amount of firm, dispatchable power, capacity wise, as we have today. So we need those technologies to complement all the variable renewables, all of the grid investments we made, all the storage, to keep things affordable.

Senator MURKOWSKI. Mr. Chairman, I am out of time. This is not an easy issue for us, but it's certainly one that we need to step into.

The CHAIRMAN. Not at all, and we will go very quickly to Senator King, and then we will come back to Senator Hawley.

Senator KING. Senator Hawley has not had a first round yet, so.

The CHAIRMAN. You have to go. You have to go preside.

Senator KING. I have to preside. Is that all right?

Thank you. Just a couple of quick questions.

Mr. Asthana, we have not talked about other technologies like demand response, and I have an expensive thermostat in my house, which I can control. I have cut my energy use in my home here in Washington by 30 percent in the last six months by using this thermostat that you can turn off during the day when you are not there. Are there other technologies that we should be talking about, and are they being sufficiently developed and utilized?

Mr. ASTHANA. Yes, I think energy efficiency, demand response, and then using the spare capacity that we have on the grid that is going to show up in the form of vehicles and batteries that are plugged in—not building that again—finding ways to reuse that when it's plugged in, I think, is going to be a big part of the future. And we are piloting those technologies. In fact, PJM has, I think, one of the premier demand-response programs in the world, and it's a key part of maintaining reliability. And I think the importance of demand response is only going to grow.

Senator KING. Thank you.

I want to join my other colleagues talking about bipartisan permitting reform. It's something we have to do in order to achieve—whatever the future looks like in terms of green energy, it's going to require building things. And Mr. Tudor pointed out, for example, we are overly dependent upon China for lithium, which is an essential part of EV batteries. So we have to talk about permitting reform in a reasonable period of time to get things done. There were some permitting reforms in the budget deal that we are talking about, voting on in the next 24 hours, hopefully, but they didn't—there is a lot that was not done. For example, transmission has to be part of it.

Mr. Robb, isn't that correct, that we really have to talk about being able to construct new transmission?

Mr. ROBB. No question, and it needs to be done much more quickly than we are able to do today.

Senator KING. And a final piece is, we have not talked too much about the pipeline system, but in New England, the gas pipeline system is part of the grid. And I believe that FERC should have more responsibility in terms of gas pipelines and reliability and

cyber protection, given the integral role that the gas pipeline system plays in the operation of the grid at the current time. Do you agree?

Mr. ROBB. I agree with that, sir.

Senator KING. Thank you.

Thank you, Mr. Chairman. Thank you, all.

The CHAIRMAN. Thank you, Senator.

Senator Hawley.

Senator HAWLEY. Thank you, Mr. Chairman. Thanks to all of the witnesses for being here. I want to particularly say hello to and welcome Mr. Tudor, of the Springfield-based Associated Electric Cooperative. I say Springfield-based, that would be Springfield, Missouri-based, which is also my hometown. So it is great to have you here, and I know the rural parts of my state, in particular, appreciate the work that Associated has done. Many times, I think, rural areas are overlooked, even when we are talking about something as important as the grid system. And so, I want to thank you for the work that you do. I was really struck by these statistics in preparing for today's hearing. Associated, your cooperative, Mr. Tudor, provides power predominantly to older individuals. Fifty-seven percent are over the age of 57, 33 percent over the age of 65 and folks on lower incomes, which is pretty typical for rural areas in Missouri and for other states. And yet, you do it at some of the most affordable rates in the nation.

Talk to us a little bit about your co-op model, why you think it works, and what we can all learn from it.

Mr. TUDOR. Thank you, sir.

We are a little bit different. Sometimes we affectionately call ourselves the unicorn. We sit, you know, between RTOs. My predecessor chose not to join an RTO years and years ago. When I arrived seven years ago at Associated, we looked at joining MISO or SPP, and we decided not to for a lot of reasons. We support the market structure, you know, we do a lot of business with MISO and SPP. We are just different. Missouri, as you know, is the "Show Me" state, and that lends itself to a significant amount of independence, and so our membership, our customers, our member-owners, our transmission owners, our management team, really believe that we prefer to operate our own assets, including our transmission system and be responsible for serving our own load.

So what is different is, in RTOs, that is all blended, where there are 100 utilities and they are least-cost dispatching, but you know, to the point of, from an affordability standpoint, we do have some of the lowest rates in the country. Our transmission rates are, you know, about a fourth of what the RTO transmission rates are, and it is because we only build transmission for load, for what our members need. It is a little different. I think that is going to change. I think we are going to have to build more transmission to facilitate more renewables all around us, otherwise we will become a linchpin for the MISO and SPP renewable development. And we are actually looking at that.

Senator HAWLEY. Let me ask you a little bit about some of the challenges you face. In your testimony, you referenced how on the one hand we are retiring dispatchable coal generation at a really pretty remarkable rate. I think it's 86,000 megawatts retired since

2011. Another 73,000 megawatts predicted by 2040. In our state, in the State of Missouri, we have relied on coal for 74 percent of the state's power as recently as 2021. So talk to me a little bit about the challenge we face when we think about wind and solar energy—more intermittent, less reliable than coal, natural gas, nuclear. How do we think about the reliability issues and address those?

Mr. TUDOR. We believe in renewables. There have been some comments earlier today. We have renewables. We have about 1,240 megawatts of wind and 500 megawatts of hydro allocation. The challenge is that during many of these weather events, we either get a lot of wind or no wind. And so, in trying to plan for weather events, when they come along, whether it be the summer or the winter, the challenge around, you know, wind and solar and batteries is that it's not four hours, it's typically days. Uri was about eight days of temperatures at zero or below. And Elliot was shorter, but the wind chills were more significant. When things got cold, we had a number of the wind farms that froze, but our fossil fuel plants, because they are already running, they have a tendency to perform better. I am not a coal guy. I am just about providing low-cost electricity to my members, and we know what works. Our fossil fuel plants work in today's environment.

In the future—I agree with many things that have been said today—and that is if we could get to an orderly transition that allows us to make changes in the type of generation that everyone relies on, we are all for that, but that generation does not exist yet. There is nothing out there to replace a coal plant. It is not there.

Senator HAWLEY. Thank you for your testimony on this. I have got some more questions I would love to ask you for the record. I appreciate what you do for my state and for Springfield and the whole region. Thank you for being here. Thanks to the witnesses for being here. And with that, Mr. Chairman, I will yield back.

The CHAIRMAN. Thank you, Senator.

We are going to have a quick second round, and Senator Hickenlooper, if you want the second round, I will come to you, and if you want to stay for a second round, if you had a real quick question.

Let me just say, first of all, everything we have talked about has been around permitting. We know where our challenges are, and anything to be done on a timely basis that you could make a determination, as you should see something coming online, and I think you all have talked about this, how desperate. We have made some inroads on permitting in the bill that we hopefully, for our debt ceiling, will pass tonight. I think we all benefit from that.

But this Committee has an awful lot more to do—an awful lot more to do on permitting. And I think everyone here has been intricate in playing that part. In a bipartisan way, we can show in this Committee how we can further our permitting process by continuing to keep our nose to the grindstone and getting this done as quickly as possible.

Just a few things. First of all, in this Committee's jurisdiction—electric transmission siting, cost allocation, interconnection queue reform, judicial review reforms for energy and mining projects, improve federal energy leasing for all types and sources, better com-

munity engagement input on project development, ensuring FERC and NERC have necessary authorities to address reliability, as we discussed today, and many other ideas we can consider that are priorities for members on both sides of this Committee, including streamlining hydrogen infrastructure, hydropower licensing, mining and oil reform, streaming LNG exports, and so much more. We are not saying by any means that we think that the bill that we are going to pass today to keep our great country paying its bills and keeping our credit rating strong has done everything that needs to be done. So I wanted all of you to know just to stay tuned, keep involved. We will be calling on you all to help us get through that, but we are going to be very vigorously involved in that process.

So now we will go with our second round.

Oh, Senator Cantwell, I am sorry. You snuck in on me.

Senator CANTWELL. Thank you.

The CHAIRMAN. Senator Cantwell, for her first round of questioning.

Senator CANTWELL. Thank you. I thank Senator Barrasso and you for holding this hearing and thanks for the recognition on this. And Mr. Chairman, you were just talking about important issues that I believe in too. I think FIVR is a great way to add affordability, help us increase the security layer, provide backhaul, middle-mile capacity, bring affordable, essential broadband to households and businesses. I was pleased to introduce legislation that you have been supportive of, Mr. Chairman, and Senator Capito has been supportive of, a bill that is supported by Edison Electric, National Rural Co-ops, and utilities.

I wanted to ask Mr. Robb and Mr. Asthana and Dr. Lott, do you agree that expanding communication capacity of the grids—existing rights-of-way—can provide significant benefits for reliability, resiliency, and modernization?

Mr. ROBB. I wasn't really prepared to talk to that issue, but I think expansion of communication accessibility for utilities, particularly in emergency response areas, is very important.

Mr. ASTHANA. Yes, I would definitely support what Jim said. I think from a communication perspective, what we really worry about is communication in a crisis, right? When the grid is down, when we are black-starting in a cyberattack, how do we communicate? And I think there is a lot of opportunity there.

Senator CANTWELL. That is why I am for a closed loop—oh, I am sorry. Go ahead, Dr. Lott.

Dr. LOTT. I was just going to say, I agree. My first recommendation is making sure that we have strong communication networks for when incidents do occur.

Senator CANTWELL. Right. And I think people don't quite grasp this—I think even some people in the Administration—that you can have a better security communication closed-loop network by doing this fiber, and so we are supportive of it.

We also want to see mandatory and comprehensive standards on millions of miles of natural gas, oil, and hazardous liquid pipelines. I will be introducing legislation to ensure that FERC has a clear role in protecting our pipelines from cyberattacks. Mr. Robb and Mr. Asthana, do you believe that the reliability of America's pipe-

line system is at risk due to the growing number of cyberattacks? Do you believe that—FERC has been setting for the bulk power sectors have increased—do you believe that the reliability and interconnection of that with the pipeline system is something that we have to address?

Mr. ROBB. I can't speak for the pipeline system broadly, but what I can tell you, Senator, is that it is absolutely clear to me that the reliability and security of the natural gas pipeline system is heavily linked to our ability to serve customers through the electric grid. So those systems are absolutely interlinked. The second point I would make is that the FERC-approved CIP standards that we have developed as NERC for the electric sector have done their job in terms of protecting the grid from cyberattacks. And then, we would be well served to expand those to address the pipeline system. And the third point I would make is that the one common denominator event in every cold weather event we have studied over the last 15 years has been fuel supply related to natural gas being available for power generators. It is a complex problem. It is not as simple as it sounds, but it needs to be addressed.

Senator CANTWELL. Thank you.

Ms. ASTHANA. Senator, I serve on the NIAC, and so we do study the linkages between the critical sectors. And I think this linkage between gas and power is critical, particularly in a cyberattack scenario, but also in a natural disaster or extreme weather scenario.

Senator CANTWELL. Great. Thank you, I appreciate that answer and what we need to do to shape it up.

Mr. Robb, during last year's heat wave in California, Pacific Northwest Hydro provided seven to eight gigawatts of energy so its neighbors could keep the lights on. How important is it to ensure that clean, reliable power can be dispatched when the grid gets distressed?

Senator Daines and I have introduced legislation, along with Senators Wyden and Risch, that would streamline and expedite hydropower relicensing to ensure the resources stay online. Do you think this idea is a good—what we are talking about here—a good proposal—the Daines-Cantwell Hydro Relicensing?

Mr. ROBB. Without knowing the details of the bill, what I will say is that hydropower is an outstanding resource. It's clean, it's dispatchable, and it plays a huge role in the Western Interconnection, as you probably know. So I think anything that can expand and secure that resource for the future is highly valuable.

Senator CANTWELL. Anybody else?

I see some nodding.

Mr. ASTHANA. The only thing I would build on Jim's answer is, in addition to run-of-river hydro, we actually have some significant pumped hydro storage, essentially batteries on our system, and I think those are incredibly valuable and we would love to see more.

Senator CANTWELL. Yes, thank you for mentioning pumped storage. Thank you.

Mr. TUDOR. I agree.

Senator CANTWELL. Okay, great.

Dr. LOTT. So briefly, we often talk about coal and natural gas as sources of firm power and also backup when demand spikes, but

hydro, nuclear, geothermal, these are also tremendous resources to provide that power.

Senator CANTWELL. Great.

Thank you very much, Mr. Chairman.

The CHAIRMAN. Thank you.

Senator Barrasso.

Senator BARRASSO. Well, thanks, Mr. Chairman.

I would just like to follow up on some of the things that Senator Hawley has been talking about to Mr. Tudor. And you know, because you are the only witness here today who runs an organization that actually produces electricity. A couple of weeks ago, you went to Wyoming, our rural electric association, where their mission—assigned mission since 1938—is to provide safe, affordable, reliable electricity to their users. It is almost becoming mission impossible with some of the threats that they are facing. So you stated that investors and insurers around the country, both in the United States and abroad, are putting pressure on electricity producers and doing it to retire coal and natural gas-fired plants prematurely. These institutions pressure cooperatives, investor-owned utilities, and others to replace the plants with weather-dependent wind and solar units.

So to what extent have government policies added to the pressure that you are facing from financial institutions?

Mr. TUDOR. It has created a significant fear factor, first of all. These—and it is, really, kind of this continual battle to try and maintain and protect our assets. The banks basically have told us over the last several years that they will stop providing us lending on coal repairs, coal assets, if we have 25 percent of our revenue coming from, in our portfolio, from coal. The insurance underwriters, both in the U.S. and Europe, are also telling us the same thing, that they are not going to insure our assets, not all of them, but many of them, again, if we have 25 percent of our revenue coming from a coal asset.

So that has narrowed the number of people we can borrow money from and the number of people that will insure our assets, which makes it more expensive. Anything more expensive is bad for our consumer-owners, who are largely rural, low-income customers.

Senator BARRASSO. Well, that was it in terms of how this affects the families that Senator Hawley was talking about, the families, the businesses who need the electricity.

Additionally, the Department of Energy is currently revising the efficiency standard for distribution transformers. The proposed standard, as I understand it, would increase the efficiency by only one tenth of one percentage point. I mean, that is negligible improvement. But yet, to meet the standards, that is going to require fundamental changes in the manufacturing process for these transformers. So you are going to be hit with all of this. This could jeopardize the availability of components needed to supply the electricity to homes and to businesses across the country. So worse yet, this proposal comes in the middle of an ongoing shortage of these transformers.

In your testimony, you said that the proposed standard “is already hindering efforts to increase the number of transformers

available.” So if the Biden Administration proposal becomes a final rule, what impact do you expect that to have?

Mr. TUDOR. I mean, this is significant. It is a horrible idea. Let me just state that. And it doesn’t move the needle, and there are so many other things that we have talked about today that are so much more important. And today, we can’t get large transformers. It is a three- to four-year time frame to get a transformer. And everything we have talked about today, in terms of infrastructure, transmission, operations, generation, all this stuff requires electricity wire, conduit, poles, transformers. So all this is going to do is slow down that whole process.

And then the real question is, we have stuff to fix now. We have a business to run and we have to repair and keep this, basically, this equipment up to date. So we have hundreds of millions of dollars that need to be spent just to keep our existing system up to speed. And then, when we start talking about adding all these new projects, renewables, that is even more infrastructure needs.

Senator BARRASSO. And when you run through this whole list of the things that you would need—does any of it come from China?

Mr. TUDOR. Yes, sir.

[Laughter.]

Senator BARRASSO. No further questions.

Thank you, Mr. Chairman.

The CHAIRMAN. Don’t need no further questions.

Senator Hickenlooper.

Senator HICKENLOOPER. Great. And again, thank you all for this.

Mr. Robb, in the debt ceiling negotiations that the Chair referred to, there was a strong interest in interregional transmission and its role promoting reliability and resilience. Can you speak to the role that interregional transmission plays in promoting reliability within the grid?

Mr. ROBB. It seems to be a very popular question I am receiving these days.

Senator HICKENLOOPER. Exactly.

Mr. ROBB. Interregional transmission is a terrific way to build resilience and reliability into the grid. It diversifies your resource base. I think David talked about the benefits that Associated has by having straws into a number of different markets and resource bases. So I think there is a tremendous amount of value to getting our head around the state of the transmission system and our ability to build resilience into the grid through expanded transmission. Whether it’s interregional transmission for reliability purposes or longer-scale projects to unlock renewables and get them to load, I think it’s a very right-minded thing for us to be very aggressive in looking at. With all the provisos that David said, the supply chain to get these projects built also needs to be solved in parallel.

Senator HICKENLOOPER. Got it.

And also, as you are aware, FERC’s got an open docket on minimum transfer capabilities, including workshops and public comments. Is NERC—are you following part of that docket, and given both Congress’s and FERC’s demonstrated interest in minimum transfer capabilities, would you be able to prioritize getting the study completed more rapidly than in the allotted time, let’s say maybe in six months or eight months?

Mr. ROBB. So to be fair, we were surprised by the provision in the bill.

Senator HICKENLOOPER. You and me both.

Mr. ROBB. We were enthused about it, but surprised about it. I think it is a right-minded thing for us to do, but I can't commit right now that I have my head fully around what it is going to take to do that project correctly. But I think it needs to be done.

Senator HICKENLOOPER. I think there is a—as we have heard today at every corner, there should be a sense of urgency.

Mr. ROBB. Yes.

Senator HICKENLOOPER. I yield back to the Chair.

The CHAIRMAN. Senator Hawley.

Senator HAWLEY. Thank you, Mr. Chairman.

Mr. Tudor, if I could just come back to you and pick up Senator Barrasso's line of questioning. He was talking to you about components in China. You said, "yes." Elaborate. What comes from China?

Mr. TUDOR. Well, when you start talking about batteries, many of the minerals come from China. You talk about solar panels, as you know, there has been an embargo against solar panels coming from China. A number of the solar panel companies are in China. So when you start bringing renewables into the mix and all these projects, part of what, you know, what Manu is talking about is, is that all these projects are sitting there in the queue, but not all of them have panels. What they have done is, they may have the land, they may have bought a transformer, you know, they have to do certain things to actually—they may have put a deposit down. But just because they put a deposit down on ten different sites in PJM doesn't mean they are ever going to build that solar. And part of the challenge is, where are you going to get the equipment, and a lot of that equipment comes from overseas, and most of it from China.

Senator HAWLEY. Is it a good idea, in general, for us to be more dependent for critical energy components on China, in your view?

Mr. TUDOR. I don't think it's a good idea.

Senator HAWLEY. I wouldn't think so either.

Let me ask you just briefly about another Biden Administration rule. This is an EPA rule that would limit carbon dioxide emissions from coal and gas power plants that they issued just last month. You mentioned this in your testimony. You said, and I am going to quote you: "The EPA has indicated that their goal is to encourage . . ." —encourage— " . . . the closure of coal and natural gas units." Let me just ask you, what do you expect the effect of those mandates will be for prices in Missouri, for example?

Mr. TUDOR. Well, there will be significant litigation against the 111(b) and (d) rules. Right now it is just a proposal. There is a 60-day time frame for all of us to make comments. I think that, first of all, is unfair for the RTOs and companies like ours, our southern company. For us to actually try and look at the effects of that in a 60-day window is, frankly, unfair.

And then, whenever they come out with the rule, that is when we have to file litigation. I think you will see significant litigation against that rule. That is money and time, and that cost—so, if you have a strategy to run someone out of business by basically taking

away their financing and their ability to insure and you increase their cost, that is a quick—and then you incent other resources. We are not pointing at anybody. If you incent other resources, what you do is you create this scenario where this is—it is picking sides. It is picking winners and losers. And I do not think we should be picking winners and losers. That is just my personal opinion.

Senator HAWLEY. Well, you know, you are the expert in this field, not me. I would just say that it seems to me that we wouldn't want to be closing down our own energy resources in this country, raising prices for our consumers, while simultaneously making ourselves dependent on China, in particular, where America gets poorer, China gets richer. That seems like a bad deal to me, whether we are talking about energy or anything else. So I kind of think we are going in the wrong direction here. And I think that your testimony points that out and highlights it. So thank you for—yes, go ahead.

Mr. TUDOR. One last point is that I don't know how you can do this, but any way that you can actually slow the EPA down, and they are supposed to have these joint discussions going on with the DOE. Anything we can do to get them understanding the significant risk they are putting our country at by forcing something that works to go away before you have something to replace it with. We have to slow them down.

That does not mean that I am against—I mean, I believe in climate change. I think the climate is changing. I just think reliability is more important. Sorry.

Senator HAWLEY. Hey, I am with you. And also, let's talk about the people who you serve, who pay the bills. You know, are we going to ask low-income folks, working people in my state to foot the bills for this Administration's climate agenda that benefits China? No thanks.

All right. Thank you, Mr. Chairman.

The CHAIRMAN. Thank you.

Let me, again, thank all of you. It was tremendous. It was, I think, very interesting. You can tell by the questions and attention that you were able to capture and hold.

One thing I will say is that transmission is going to be a challenging thing for us. We have some states that do not want to be involved because they have a pretty good monopoly. And we understand that. And we want to make sure that they are protected, but also, be part of this as we have to be able to, you know, move these electrons. So we are going to ask for your input and thoughts. Anything you want to submit to the Committee on how you think we can navigate the transmission by not encroaching and basically changing someone's whole business model. That is not our intention.

And I want to make sure that these states that have these tremendous delivery systems, I think you all know which ones I am talking about, but these are all our friends. We want to make sure they have the opportunity to do what needs to be done for us to move the electrons that need to be moved. We are going to need your input to make that happen because right now it will be challenging, but without transmission, we are not going to be able to move, whether it's fossil or whether it's renewables. We can't move

it. We know that, and we are not going to meet any deadlines whatsoever.

And I think if you—the most interesting meeting I had in my office—about a month ago, I came in and there was a group of military people from Germany. They said, we came to explain to you, if you want to know what not to do with your energy grid, look at what we did. We did the wrong thing. We took things offline before we had anything to replace it and became totally dependent on Russian energy—oil, and gas—cheap. It's like a dope dealer. They get addicted to it. And basically, they are paying a heck of a price right now and we are doing everything we can to give them the support, but we have to be energy secure. That is the most important thing.

And I think that with the debt ceiling today, I am very appreciative. Democracy is working well. You have Democrats and Republicans both joining forces, which we will do hopefully sometime today, tonight, whenever. But you know, I believe in this great country and the process we have, even though it gets quite challenging at times. Don't give up, okay? But we need your input.

So with that, members will have until the close of business tomorrow to submit additional questions for the record.

With that, the meeting is adjourned.

[Whereupon, at 12:11 p.m., the Committee was adjourned.]

APPENDIX MATERIAL SUBMITTED

U.S. Senate Committee on Energy and Natural Resources
June 1, 2023 Hearing: *The Reliability and Resiliency of Electric Service*
in the United States in Light of Recent Reliability Assessments and Alerts
Questions for the Record Submitted to Mr. David J. Tudor

Questions from Ranking Member John Barrasso

Question 1: Dr. Lott argued in her prepared testimony that it would be useful for Congress to strengthen requirements for risk assessment and mitigation planning in power sector planning processes to help “design a system that will be reliable, resilient and affordable moving forward.” Accurate modeling and evaluation of these risks when planning for the deployment of new generation is a useful tool in avoiding reliability events.

- a. As the only witness who is tasked with producing electricity, has your organization conducted an analysis on the effect or potential effect of the adoption of large-scale intermittent generation in and on your service territory?

Associated Electric uses its resource planning team, resources, expertise and third-party sources to inform and produce an annual integrated resource plan that models the use and impacts of various generation sources near- and long-term. These internal resource plans are projections that take into account many assumptions and variables, including the current and future adoption of intermittent generation by Associated, regional transmission organizations and other entities connected to the Associated system. The potential effect of the rapid deployment of intermittent resources are captured in the ongoing integrated resource planning process and its outputs. As captured in my original written testimony, the rapid adoption of intermittent generation that displaces reliable baseload generation results in a less reliable overall system that will be prone to more reliability challenges.

- b. If so, have you relied upon the help of a third-party organizations or experts to conduct or inform the analysis?

Associated uses its active participation in industry associations, like the Electric Power Research Institute (EPRI) to inform our planning. I presently serve on the EPRI board of directors.

EPRI is leading a new, three-year initiative, Climate READi™: Power (REsilience and ADaptation Initiative, convening global thought leaders and industry stakeholders to develop a common framework to assess risk and address challenges. The Climate READi framework produced from this effort will embody one of the most comprehensive, integrated approaches to physical climate risk assessment.

Climate READi enables global energy companies, climate scientists, regulators, and other stakeholders to proactively analyze and apply climate data, allowing for the planning, design, and operation of resilient energy systems of the future. There are 13 founding Climate READi members: Alliant Energy Corporation, Ameren Corporation, American Electric Power, Consolidated Edison Co. of New York, Exelon Corporation, National Grid PLC, New York Power Authority, Pacific Gas & Electric, Portland

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General Electric, Puget Sound Energy, Southern California Edison, Southern Company, and WEC Energy Group.

More information can be found at EPRI's Climate READi online resource portal: <https://www.epri.com/research/sectors/readi>. This EPRI-produced video provides a high-level overview of the initiative: <https://youtu.be/99NyIVmymE>.

More specific to Associated's region, the cooperative also participated in a 2021 MIT Center for Energy and Environmental Policy Research study specifically conducted to assess impacts of decarbonization of power systems in Associated's region; [Challenges and Opportunities for Decarbonizing Power Systems in the US Midcontinent - CEEPR CEEPR \(mit.edu\)](#).

c. If so, what were the findings?

EPRI's Climate READi is a global initiative in its second year of a proposed three-year mission. The framework for comprehensive information gathering and stakeholder involvement has been set and workstreams established to enable participants to better assess risks and prepare for an energy transition to a low-carbon future. Future findings are still to be determined.

In the MIT study of the Midwest region cited above, the study findings include the following impacts:

- All decarbonization scenarios involve wind and solar generation displacing coal and fuel oil power plants to a greater or lesser extent, depending on the level of decarbonization and the type of policy.
- Natural gas generation remains in the system to support the integration of renewable generation, again to a greater or lesser extent, depending on the level of decarbonization and the type of policy.
- Nuclear generation remains central if the policy is to be cost efficient.
- Batteries remain a marginal technology.
- These levels of renewable penetration produce important challenges system managers will have to meet in order to maintain reliability.
- Decarbonization creates more volatility in system marginal cost, with more scarcity hours and more hours of zero or negative marginal cost. This suggests a need for implementation of capacity mechanisms to reduce perceived risks in financing capacity.
- A specific decarbonization policy can generate local distress for certain entities, e.g. cooperatives, suggesting a need for cooperation and agreement among all relevant stakeholders, potentially flanked by compensation payments.

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- d. How do you define or consider “extreme weather” in your modeling and daily operations?

Extreme weather for our system involves ambient conditions resulting in high electric consumption for heating or cooling, typically observed in multi-day events during peak seasons. As electrification of space heating grows, peak system load variations in winter have become far more extreme than in summer, often coinciding in hours of the day with little or no sunlight or wind availability.

- e. How do you plan for weather events?

Associated’s top priority in planning is to ensure enough power can be supplied to our system on a peak demand day. This premise infuses our integrated resource plan and day-to-day mindset. Impending extreme weather is monitored and planned for operationally and through an extensive power marketing program.

Associated proactively hardens its generating assets to protect against extreme weather by going through extensive seasonal (summer and winter) checklists at each of its generating stations to reduce operational risk to the extent possible. Based on the situation, power purchases with firm delivery are arranged in advance of potential events to ensure we can meet our member load and system contingency requirements. Native generation and power purchases both play critical roles if member energy load exceeds supply and/or generating assets, fuel supply or other parts of the energy generation process are comprised.

As peak events unfold, operational and marketing arms of the cooperative make decisions and adjustments in real-time with reliability as the top priority, followed closely by keeping costs as affordable as possible in a likely environment of higher expense for fuel (natural gas), power purchases, labor and other expenses. For example, generating assets may be started and placed online in advance of the onset of severe weather to minimize start-up problems and ensure their availability. Associated power marketing arranges for firm power supply in advance and manages market interactions in real-time with reliability and costs as priorities to safeguard members.

- f. What recommendations do you have with respect to mitigating the worst effects of extreme weather?

Perhaps the ultimate mitigation strategy is the operation of our baseload generating assets, in particular coal plants, due to their long-term fuel supply stored on site. With a target of 45 days of fuel on the ground at each coal plant location, fuel security shields these generators from supply disruptions during long durations of high energy demand. During recent winter storms Elliot in 2022 and Uri in 2021, coal generation proved to be

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the difference in reliably serving members versus resorting to rolling blackouts. Baseload generating units, designed to stay online for long run-times to serve load, are a proven foundation for reliability that can serve as a bridge until other technologies are feasible.

- g. What “mitigation planning” from your perspective will be necessary if the retirements you project occur on the timetable you suggest?

The first and best mitigation strategy is to retain baseload generation for as long as possible. Second, the addition of new, dispatchable natural gas peaking generation is a logical strategy for Associated’s system to keep pace with growing demand. Permitting timelines and environmental constraints continue to challenge the addition of reliable peaking generation in time to serve an increasingly volatile electric system with increasing intermittency and growing energy demand. So, a third enabling strategy is to expedite permitting to enable additions of natural gas units by 2028, in time to meet the planned retirements of coal units.

Finally, as stated in my earlier testimony, if the breadth and pace of baseload generation retirements continues as projected, a less reliable electric system for consumers is inevitable. Compromised reliability during high demand will become the new normal—something no one wants. A strong tie between federal policies incentivizing baseload retirements and intermittent power sources and mandatory study of corresponding impacts to reliability would provide a much-needed dose of reality to any energy transition and limit potential consumer harm. That tie between energy policy and reliability impacts is noticeably absent in the current process.

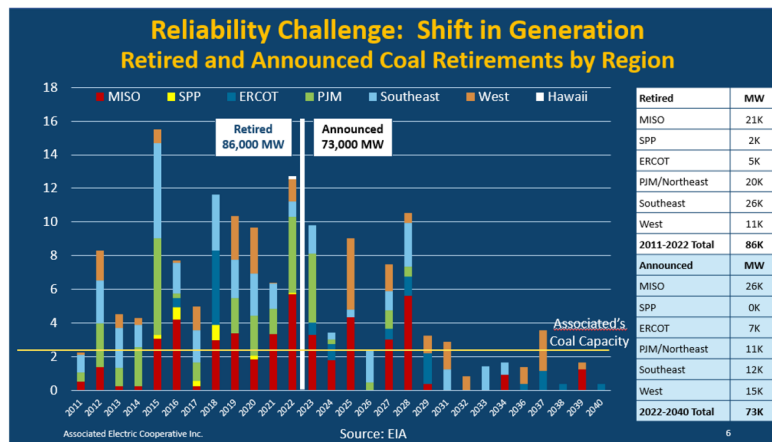
Question 2: Throughout the hearing, Mr. James Robb, President and CEO of the North American Electric Reliability Corporation (“NERC”), Manu Asthana, President and CEO of PJM, and several Senators agreed with your assertion that premature retirement of dispatchable power represents a known and growing risk to the grid. You have testified that many coal units will be retired by 2028. That is well before the date that any new emission-free technology capable of being dispatched at will by power system operators will come into service. You said that these retirements will be driven, at least in part, by new regulations currently being considered by the Environmental Protection Agency (“EPA”).

- a. What do you see as the likely pace of coal retirements in the United States?

Based on publicly available data from the U.S. Energy Information Administration, the pace of domestic coal generation retirements will continue at a fast and, in our estimation, ill-advised pace that is out of sync with the development of realistic alternatives to replace reliable baseload generation. From 2023 - 2040, 73,000 additional megawatts will be retired, joining 86,000 megawatts already retired from 2011 to 2022 (*see chart: Reliability Challenge: Shift in Generation*). Coal combustion residual and effluent regulations designed

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to close existing waste disposal impoundments at coal plants must be satisfied by 2028, or those plants will be forced to close, which will hasten retirements for some in the industry. The retirement pace slows after 2028, when most announced closures are projected to be complete. As shown in written testimony, the majority of planned future generation to replace coal plant retirements are intermittent sources: wind, solar and batteries.



- b. How do you project EPA rulemakings will lead to the premature retirement of coal units?

The EPA's policies and rules on multiple fronts do not take into account the impact to reliability and the real-world implications of replacing reliable, baseload generating resources like coal and natural gas with intermittent resources like wind, solar and batteries. Any effective energy transition that does no harm to consumers will require technologies not yet available to replicate the reliability of fossil fuel plants and a substantial build-out of the high-voltage transmission system to move renewable power from where it is generated to where it will be used. Finally, the timeline and target dates must be realistic, not arbitrary, to ensure technology breakthroughs and transmission development can reliably support such a transition.

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- c. What do you expect the result of such retirements to be?

Premature baseload generation retirements, absent a replacement technology that effectively replicates its characteristics, will lead to compromised reliability. This inevitable conclusion mirrors the findings in the NERC 2022 Long-Term Reliability Assessment and 2023 Summer Reliability Assessment. The majority of the country will find itself in areas of elevated or high risk for reliability problems as soon as summer 2023. Those problems could include public conservation appeals, warnings, alerts and ultimately planned service interruptions – rolling blackouts – to maintain the integrity of the overall electric system.

- d. Do you know of any resource that will be available before 2028 that has the attributes of today's coal plants?

No. The most likely candidate for effective no-emissions replacement of coal and natural gas generation is small modular nuclear reactor (SMR) technology. At present, the projection is for the first-ever SMR unit to go online in 2030; that unit will be heavily scrutinized for its overall performance and cost profile. Current cost projections for this new type of nuclear power are roughly 100 times the cost of keeping open traditional baseload generation.

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