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Committee on Science, Space, and Technology

United States House of Representatives

Lessons Learned from the Texas Blackouts: Research Needs for a Secure and Resilient Grid

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My name is Jesse Jenkins. I am an energy systems engineer and an assistant professor at Princeton University with a joint appointment in the Department of Mechanical and Aerospace Engineering and the Andlinger Center for Energy and Environment. I am also an affiliated faculty at the Center for Policy Research in Energy and Environment at Princeton's School of Public and International Affairs and at the High Meadows Environment Institute.

My research focuses on the rapidly evolving electricity sector, including the transition to zero-carbon resources, the proliferation of distributed energy resources, and the role of electricity in economy-wide decarbonization.

Let me first describe my professional background and qualifications. I received a PhD in Engineering Systems and S.M. in Technology and Policy from the Massachusetts Institute of Technology and a B.S. in Computer and Information Science from the University of Oregon. I have served previously as a postdoctoral Environmental Fellow at the Harvard Kennedy School and the Harvard University Center for the Environment, a researcher at the MIT Energy Initiative, a research fellow at Argonne National Laboratory, the Director of Energy and Climate Policy at the Breakthrough Institute, and a Policy and Research Associate at Renewable Northwest. Since 2012, I have also provided decision support, analytics, and policy advisory services to various non-profit and for-profit clients working to accelerate the deployment of clean energy. I have published thirteen peer reviewed journal articles as well as multiple working papers, technical reports, and policy briefs. I am one of the principle investigators of the recently-released Princeton *Net-Zero America* study and currently serve as a member of the National Academies of Science Engineering and Medicine (NASEM) Committee on *Accelerating Decarbonization of the U.S. Energy System*.

The views expressed in this testimony are my own, and I am not speaking as an official representative of Princeton University, the NASEM Committee, or any of my co-authors or consulting clients.

I would like to thank Chair Johnson, Ranking Member Lucas, and the members of the Committee for inviting this testimony. I commend the Committee for holding this hearing and for trying to get to the bottom of what went wrong in Texas during last month's extreme cold—and for working to identify what this Committee and Congress can do to better prepare all Americans for similar threats.

The truth is there is plenty of blame to go around. Failures to plan for and build resilience to this extreme cold were systemic. All sources of power experienced failures from natural gas and coal plants to wind turbines and even one of the state's four nuclear reactors. Natural gas wells and pipelines froze, cutting off gas supply just as it was needed most. And state and federal policymakers alike all failed to require more robust winterization measures after a 2011 winter storm triggered blackouts and provided ample warning of the fragility of Texas's energy infrastructure to extreme cold.

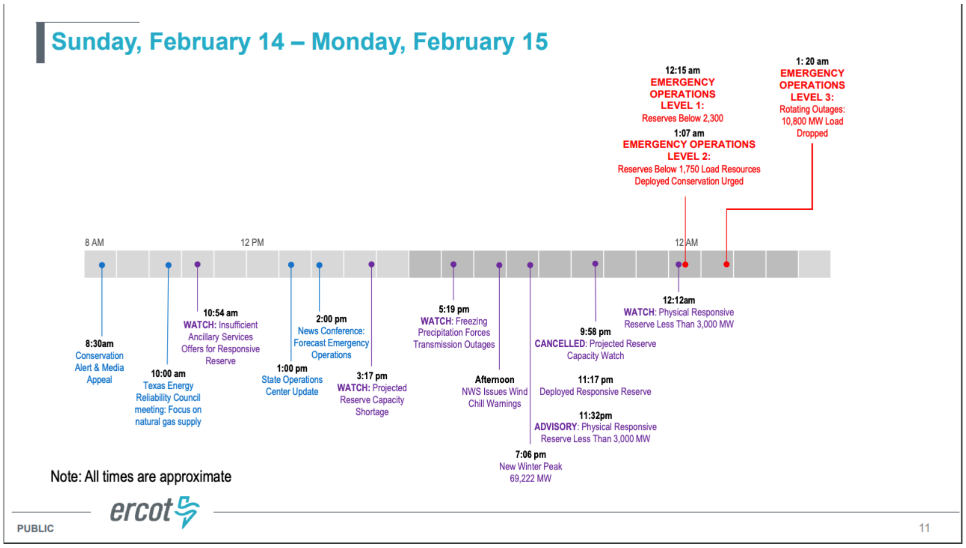
These systemic failures make it all too easy to cherry-pick claims that advance one's preferred narrative or confirm one's priors. The dozens of Texans who died and the millions who suffered through the days-long crisis – many of whom are still rebuilding today – deserve a full account of what went wrong. Americans all across the country in each of your districts can learn from the Texas crisis and take steps to prepare for the extreme weather threats we all face, threats that climate change is making more severe.

1. What went wrong

The general factors behind Texas's grid failure are now well understood—although a full timeline of all critical details on what caused specific power plant and gas system failures is still not available at this time.

What we know is that on February 14th, a rare burst of Arctic air spread across the central U.S. and into Texas, dropping temperatures there into the single digits and sending electricity demand to a new winter peak of 69,222 megawatts (MW), nearly 5% higher than both the previous record and the "Extreme Peak Load" scenario considered by the Texas grid operator, ERCOT, in its winter reliability plan.

That was before temps dropped even further overnight, sending the entire state under a winter storm warning for the first time and setting new record cold temperatures everywhere from Lubbock to Corpus Christi.



Sunday, February 14 – Monday, February 15

8:30am Conservation Alert & Media Appeal

10:00 am Texas Energy Reliability Council meeting: Focus on natural gas supply

10:54 am **WATCH:** Insufficient Ancillary Services Offers for Responsive Reserve

1:00 pm State Operations Center Update

2:00 pm News Conference: Forecast Emergency Operations

3:17 pm **WATCH:** Projected Reserve Capacity Shortage

5:19 pm **WATCH**: Freezing Precipitation Forces Transmission Outages

Afternoon NWS Issues Wind Chill Warnings

7:06 pm New Winter Peak 69,222 MW

9:58 pm **CANCELLED**: Projected Reserve Capacity Watch

11:17 pm Deployed Responsive Reserve

11:32pm **ADVISORY**: Physical Responsive Reserve Less Than 3,000 MW

12:12am **WATCH**: Physical Responsive Reserve Less Than 3,000 MW

12:15 am **EMERGENCY OPERATIONS LEVEL 1:** Reserves Below 2,300

1:07 am **EMERGENCY OPERATIONS LEVEL 2:** Reserves Below 1,750 Load Resources Deployed Conservation Urged

1: 20 am **EMERGENCY OPERATIONS LEVEL 3:** Rotating Outages: 10,800 MW Load Dropped

Note: All times are approximate

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Figure 1. Timeline of the start of the Texas electricity system crisis on February 14th-15th. Source: ERCOT.

Very early on February 15th, things fell apart. Shortly after midnight, about 8,000 MW of natural gas power plants and 2,000 MW of wind turbines were forced offline by the cold.

ERCOT deployed system operating reserves, which are standby generators prepared to ramp up to compensate for this kind of unplanned outage. The system remained stable, but entered emergency operations, as now-depleted reserves left the system in a fragile state.

The next hour, 1:00-2:00am, nearly brought the entire Texas grid down. Several thousand more MW of natural gas and coal power plants failed in rapid succession. By 1:25am Monday, over 30,000 megawatts of thermal power plants were offline, more than 40% of the total needed to meet demand — and more than twice level ERCOT considered in an “Extreme Generator Outage” winter planning scenario.

Faced with record demand, depleted operating reserves, and far less generation than the “extreme” scenarios they’d planned for, ERCOT had no choice but to order transmission utilities to start emergency disconnections of millions of customers. Many of them would go without power for days.

The central challenge is that electricity supply and demand have to be kept in balance at all times. If demand exceeds supply, generators strain to meet the greater load, which results in a decline in the frequency at which the alternating current grid reverses polarity (60 hertz, or 60 times per second during normal operations) as synchronized generators slow their rotation under the strain. If the imbalance is too large and frequency drops less than 1% below the nominal 60 hertz (or less than 59.4 hertz) for more than a few minutes, generators will automatically disconnect to avoid damage, triggering a cascading failure that can result in a total systemwide blackout. A grid operator’s primary duty is to avoid this outcome.

According to ERCOT, the Texas grid was just “minutes and second away” from this total system failure. If that scenario had occurred, it could have left Texans without electricity for weeks, requiring a “black start,” a delicately orchestrated operation to carefully bring power plants and transmission lines back, one-by-one. While ERCOT and other system operators drill and plan for black starts, the operation has never actually been performed, as the Texas grid has never suffered a complete system-wide blackout.

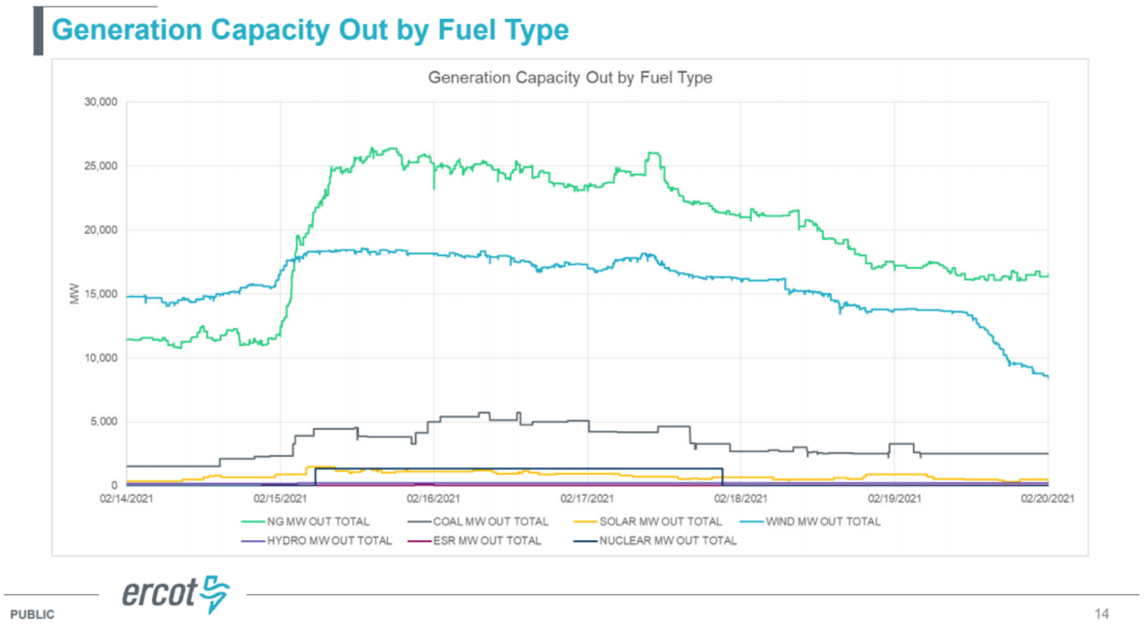


Figure 2. Timeline of generation capacity outages reported to ERCOT. Note that wind and solar power capacity outages are reported against maximum rated capacity, but ERCOT does not plan on wind or solar resources to supply this much generation during winter peak load events. In their Winter Seasonal Assessment of Resource Adequacy (SARA) report, ERCOT 'derates' wind capacity to about 25% of installed capacity on average (varying by location) and solar to 7% on average, and it plans for as little as zero solar and less than 6% of installed wind capacity in 'extreme' low wind output scenarios. ERCOT also plans for about 4,000 MW of planned maintenance outages for thermal power plants (natural gas, coal and nuclear) during winter peak demand periods; 32,000 MW of thermal outages were reported at maximum. Source: ERCOT

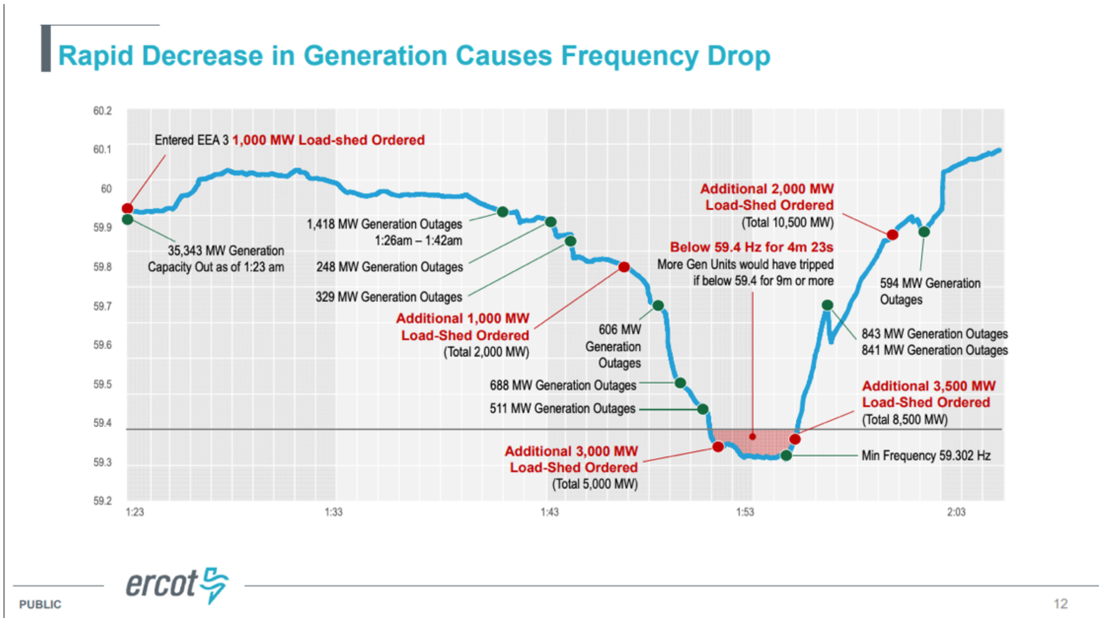


Figure 3. ERCOT system frequency (in hertz) during the height of the grid crisis, circa 1:00-2:00am, February 15th. *If alternating current frequency drops less than 1 percent below the nominal 60 hertz (or less than 59.4 hertz) for more than a few minutes, generators will automatically disconnect to avoid damage, triggering a cascading failure that can result in a total systemwide blackout. Source: ERCOT*

The specific causes of generator outages during the night of February 15th remain unknown, as investigations continue and we wait for ERCOT to release more detailed reports on what triggered plant failures, where, and when. These details will be critical to precisely diagnose the chain of events and understand where along that chain interventions could have prevented the blackouts.

We do know that all sources of power generation were hammered by the storm, and all failed to some degree.

Wind turbines and coal piles iced up. Other power plants were knocked offline by frozen feedwater pipes, instrumentation, valves, and other equipment. For example, one of the state's four nuclear reactors, a 1,300 MW reactor at the South Texas Station half way between Houston and Corpus Christi, went offline for about 36 hours due to a frozen sensor on a feedwater pipe that supplies coolant water for the plant, triggering faulty sensor readings that forced a precautionary shutdown of the reactor. There was no real imminent danger, but reactor operators are extremely cautious, requiring the shutdown until the instrumentation could be restored.

Critically, the energy system failures were not the power grid's alone. Texas's abundant but liquids-rich natural gas fields saw wells and gathering lines freeze up, which cut gas field production in the state in half. Dozens of compressor stations along the gas pipeline system built during Texas's recent natural gas boom apparently failed to register with the transmission utilities as "critical loads," and many thus lost power during the blackouts, further exacerbating the gas supply shortages. Gas delivery pipelines can also freeze off, as water in the lines turns to ice, causing pressure swings that force pipelines to shut down to ensure safety.

The greatest share of power generation outages were at natural gas power plants, which the state relies on for about two-thirds of its winter peaking capacity. How much of this capacity was lost due to failures in gas supply wells and pipeline networks and how much was due to failures at the power plants themselves is still not clear. But what is clear is that this loss of over 26,000 MW of gas-fired capacity was the single biggest contributor to the Texas blackouts.

2. The cost of extreme weather and the value of resilience

In the end, a state known for its abundant energy resources experienced widespread failures of natural gas and electricity systems that left more than 4.5 million Texans without power, most of them for several days. The winter storm, the coldest in 30 years, left dozens dead and caused about $155 billion in damages and economic losses ($130 billion in Texas), according to estimates from AccuWeather. That rivals the economic toll of Hurricane

Harvey in 2017, and is nearly 2.5-times larger than the cost of the entire Atlantic basin hurricane season.

With such a devastating toll, the Texas blackouts are a tragic reminder of the sometimes-deadly fragility of our critical infrastructure systems during extreme weather conditions.

The challenge is that critical infrastructure is resilient *only up to a point*. When pushed a little bit further – a few degrees colder or hotter, an inch more rain, a day longer drought – these systems can fail in catastrophic ways. Investment and action to push back that point of failure – and to prepare response strategies that mitigate the harms when systems do fail – can be well worth it.

Extreme weather tends to cause multiple parts of critical systems to fail at the same time. These kinds of simultaneous (or correlated) failures are far more probable and dangerous than one might think. If 10 power plants each have a 10% chance of failure but these probabilities are all independent, the chance that they all fail simultaneously is infinitesimal (0.00000001%). A 1% chance (equal to the probability of a once-in-a-century storm) that 10 power plants all fail at once is far more worrisome.

Building resilient infrastructure means paying close attention to extreme events that can slam large parts of the system all at once, whether that's a winter storm, wildfire, hurricane, or flood.

While the scientific jury is still out on whether these 'polar vortex' cold snaps are related to climate change, we do know that climate change increases the frequency of extreme heat waves, droughts, wildfires, rainfall events and coastal flooding. And it is these extreme events that test our systems to the breaking point, just as they did in Texas last month.

This is the Science & Technology Committee, so questions of R&D and new innovations will deservedly be at the center of discussion during today's hearing. But at some level, the Texas crisis was not a failure of technology, per se.

Energy systems can and should be made more resilient to extreme weather with existing technology. After all, wind turbines operate today in Antarctica, gas plants in Alberta, and gas wells in Alaska.

Weatherization can be costly, but the most affordable steps, such as winterizing wind turbines or using heat tracing to keep pressure sensors from freezing up at natural gas or nuclear power plants, can be well worth it.

More costly measures could include burying gas-field gathering lines to insulate against the cold surface and housing gas wells and liquids separation facilities in heated buildings. "Dual fuel" power plants can switch from gas to petroleum stored on site when gas supplies are disrupted. Long-distance power lines can link up with far away regions facing less severe challenges.

All of this is possible with current technology, but all of it comes at an added cost, a cost paid every year in the hopes that devastating but rare crises are avoided.

In this way, building resilience to extreme events is a bit like buying fire insurance for your home.

Most of us buy insurance not because we ever expect our home to burn down. But we know that if such a tragedy should occur, however rare, the results would be catastrophic. Without insurance, we'd lose everything and building our lives back may be impossible. So, we pay the premium every year, even though we don't ever expect to use it.

If a crisis does strike, paying the premiums can look like the perfect decision in hindsight.

The problem, of course, is that we have to plan using our foresight, not hindsight. Determining how much 'insurance' – in the form of investment in grid resilience – is worth it and what kinds of crises we wish to protect against is the key challenge.

Texas is well prepared for summertime peaks in demand driven by heat waves, just as New England is well prepared for winter cold and gas supply shortages. These happen frequently enough that it's clear we must make investments to mitigate these risks. Planning for rarer events is much more difficult.

But just as with the decision to purchase fire insurance, the calculus should come down to not only how frequent such events are but also *how severe their impacts are when they occur*. A once-in-a-decade cold snap or heat wave that causes a few hours of rotating blackouts may be something we can live with. But as the Texas crisis reveals, several days without power and heat during sub-freezing temperatures costs far too much in both lives lost and economic damages incurred.

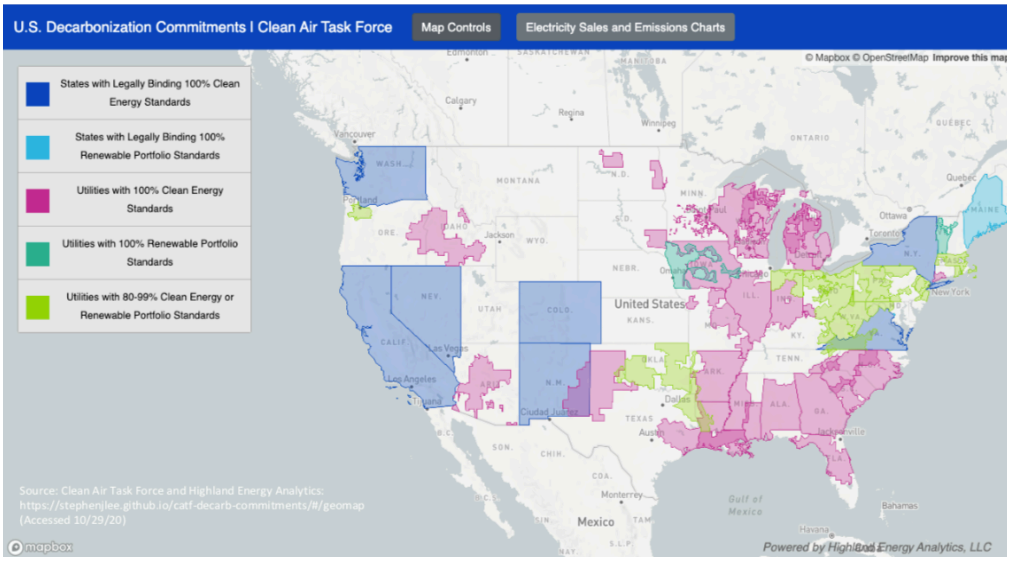
The changing climate makes planning and building resilience more difficult, as it means the past is no longer a safe guide to the future. The entire country must get much better at preparing for the unexpected.

Going forward, any new infrastructure we invest in should be prepared for not only today's climate, but also the climate we'll have decades into the future. For each upgrade we make, we must decide what range of climate extremes it should be able to withstand.

This is where research can make a difference. Expanded investment in climate science could help planners build more resilient systems. The focus of this research should be on assessing impacts on critical infrastructures and proactively identifying failure modes that can bring correlated or simultaneous failures of the kind experienced in Texas.

3. Building a resilient and affordable clean electricity system.

The U.S. electricity system in transition. About half of all U.S. electricity sales are now covered by states or electric utilities that have now committed to transition to 100% clean electricity. Federal legislation requiring a transition to 100% clean electricity nationwide has also been introduced. The direction of travel towards a 100% carbon-free grid is clear, even if the pace remains uncertain.



Source: Clean Air Task Force and Highland Energy Analytics: https://stephenjlee.github.io/catf-decarb-commitments/#/geomap (Accessed 10/29/20)

Percent of Total US Electricity Sales Accounted for by Selected State Legislation and Utility Pledges

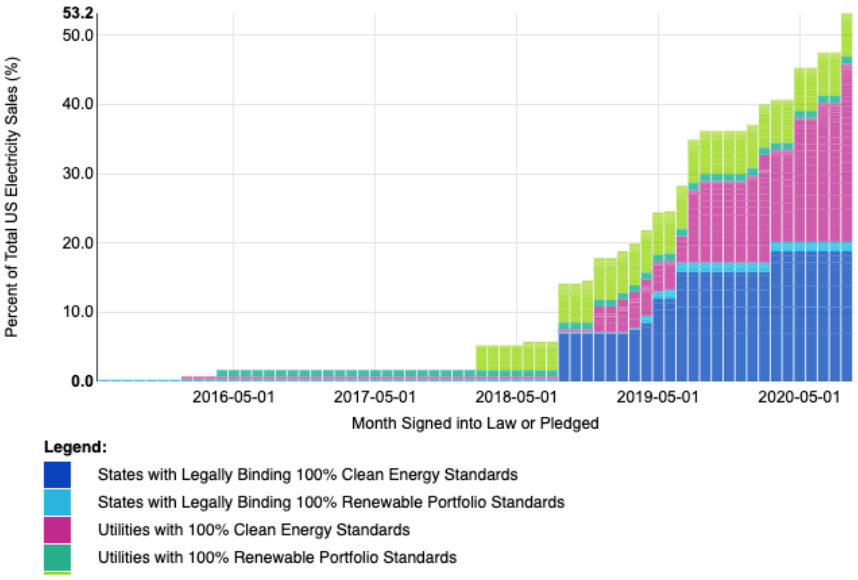


Figure 4. States with legally binding 100% clean energy or renewable energy requirements and utilities with voluntary commitments to transition to overwhelmingly clean electricity supplies. *These commitments now cover about half of all U.S. retail sales of electricity. Source: Clean Air Task Force and Highland Energy Analytics.*

This transition is critical, because clean electricity is the linchpin in any successful and affordable transition to a net-zero emissions U.S. economy by 2050 or sooner. As the National Academies study on *Accelerating Decarbonization of the U.S. Energy System* makes clear, pathways to cost-effectively reach net-zero greenhouse emissions entail twin challenges for the electricity sector:

1. As the source of more than a quarter of U.S. greenhouse gas emissions and with multiple scalable, affordable alternatives to fossil fueled power plants available today, the electricity sector must (and can) cut emissions faster and deeper than any other sector.

2. Electricity generation must substantially expand—approximately 10−20% by 2030 and 120−170% by 2050—to fuel a greater share of energy use in transportation, building space heating, and low- and medium-temperature industrial process heat as well as produce hydrogen from electrolysis and even power direct air capture.

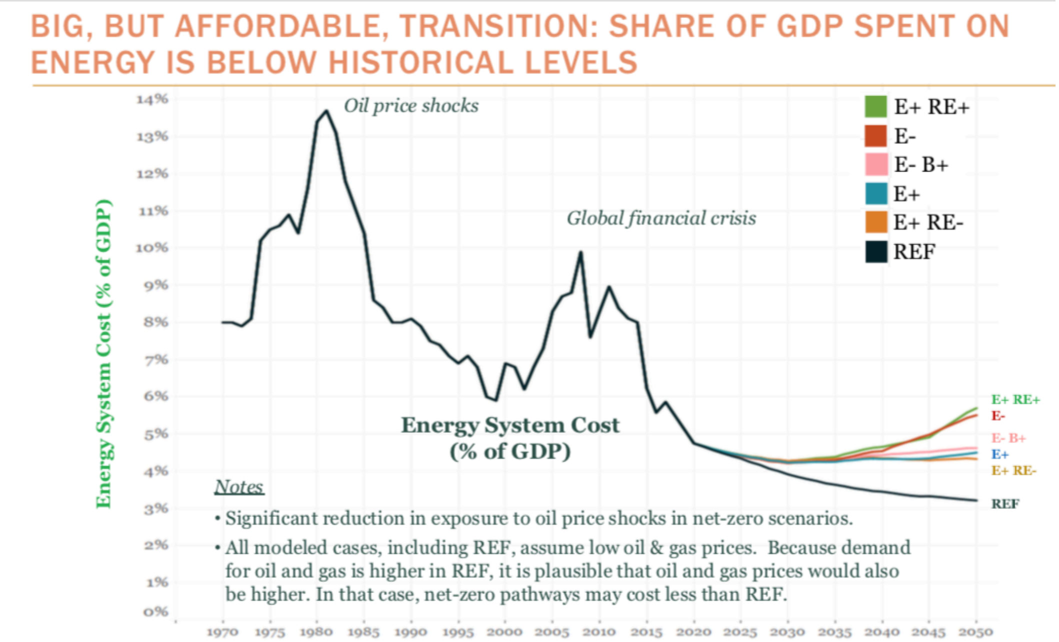
Rapidly reduce greenhouse gas emissions and transitioning to net-zero emissions nationwide is a critical and achievable goal. Until we reach net-zero emissions globally, the concentration of climate-warming gases will continue to increase, destabilizing our weather and driving more frequent and severe extreme events that are electricity systems and other critical infrastructure are so vulnerable to.

The U.S. can and should lead in this transition. We have the economic and technical means to do so, and our leadership can not do our part to reduce our share of global emissions, but can also serve to drive the American ingenuity and innovation that will make clean energy and climate solutions affordable and available for the world.

The Princeton *Net-Zero America* study, for which I served as co-principal investigator, concluded that this transition to net-zero emissions and 100% carbon-free electricity is an enormous national undertaking, but one that is ultimately affordable.

We modeled and analyzed with unprecedented granularity five distinct pathways to affordably reach net-zero economy-wide by 2050. These paths all rely on technologies we fundamentally know how to build today, although several require continued innovation and cost declines to realize their full potential, and none depend on widescale behavioral changes such as shifts to vegetarian diets or major reductions in vehicle travel.

The *Net-Zero America* study concludes that all of these paths to net-zero emissions require spending no more (and in many case less) as a share of our national gross domestic product on energy services as we do today. In other words, getting to net-zero does not require widespread economic sacrifice or a World War Two style mobilization of 20% of our GDP to build a clean energy infrastructure. Instead, we need to continue spending about the same amount of our household and business expenditures on energy as we do today, but shift our investments towards cleaner sources of electricity and other energy sources.


BIG, BUT AFFORDABLE, TRANSITION: SHARE OF GDP SPENT ON ENERGY IS BELOW HISTORICAL LEVELS

Notes
- Significant reduction in exposure to oil price shocks in net-zero scenarios.
- All modeled cases, including REF, assume low oil & gas prices. Because demand for oil and gas is higher in REF, it is plausible that oil and gas prices would also be higher. In that case, net-zero pathways may cost less than REF.

Figure 5. Annual energy expenditures as a share of U.S. gross domestic product (GDP) under five modeled pathways to net-zero greenhouse gas emissions economy-wide by 2050. *Source: Princeton Net-Zero America study.*

The benefits of this transition are also large, including half a million to a million *net* jobs created in energy supply related sectors by 2030 and 2-3 million by 2050, as well as $2-3 trillion dollars in public health damages and 200,000-300,000 premature deaths from air pollution avoided from 2021-2050.

The findings of the *Net-Zero America* study should build confidence that by deploying the clean energy technologies we have today *and* continuing to drive the innovation and improvement in technology that this committee has worked so hard to accelerate, we can reach net-zero while spending a similar share of GDP on energy services as we do today.

Our modeling for the *Net-Zero America* study and most other research on electricity systems today repeatedly finds that wind and solar power can be cornerstones in an affordable and clean electricity system.

Wind and solar power are now cheap. Thanks to proactive public policy support and innovation, the cost of wind power has fallen by about 70% and the cost of solar by about 90% over the last decade alone, and cost declines are projected to continue into the future. This increasingly makes wind and solar the cheapest source of electricity we can use, period.

Yet during the Texas crisis, wind and solar power provided at times as little as 1,000 MW of output, a tiny fraction of the more than 30,000 MW of installed capacity. That performance during the winter storm has led some to question: Can we assure a clean *and* resilient grid with a larger role for wind and solar power?

The answer is yes. To understand why, we need to understand the role of each resource in the electricity system.

We don't need every source of electricity to be reliable all the time. What we need is the *system* to be reliable, and that requires a mix of electricity resources all playing the right role on the electricity team.

Wind and solar don't deliver value by being dependable, and this should come as no surprise to anyone.

The simple truth is that wind and solar are reliably unreliable. We *know* the wind is inconstant and that nights affect solar output. Grid planners, including ERCOT, thus heavily discount the contribution of wind and solar during peak demand or extreme weather conditions. And they should.

The fact that wind and solar are unreliable does *not* mean they have no value. This simply isn't their job.

Wind and solar deliver real value to electricity systems and ratepayers as fuel-saving resources. When available, wind and solar power are the cheapest ways we have to produce electricity. Without fuel, they are nearly free on the margin; when the wind is blowing and the sun is shining, these resources displace costlier sources of electricity, namely from fuel consuming resources like natural gas and coal. That saves billions of dollars and helps reduce the carbon dioxide emissions fueling more extreme weather that threatens the resilience of our electricity systems.

Remember that Texas has no mandate for wind or solar power. The state was one of the first states implement a renewable portfolio standard in 1999, requiring 5,000 MW of wind power by 2015 and 10,000 MW by 2025, but Texas surpassed this 2025 target fourteen years early in 2009. Since then, every single megawatt of wind or solar power installed in the state has been installed because it makes more money for its investors and saves more money for Texas electricity consumers than any alternative. Wind and solar aren't chosen because of onerous regulations, but because they make economic sense.

What every power system with a bigger role for wind and solar need is to maintain sufficient firm generating capacity to deliver necessary reliability.

Firm electricity resources are available on demand, any time of the year, for as long as needed.[1]

These characteristics make firm resources a critical complement to weather-dependent variable renewable energy sources like wind and solar power, as well as resources such as batteries or strategies like demand flexibility (which permits consumers to reduce their electricity use in periods when supplies are strained) that are best suited to fast bursts of use, rather than sustained output over days or weeks.

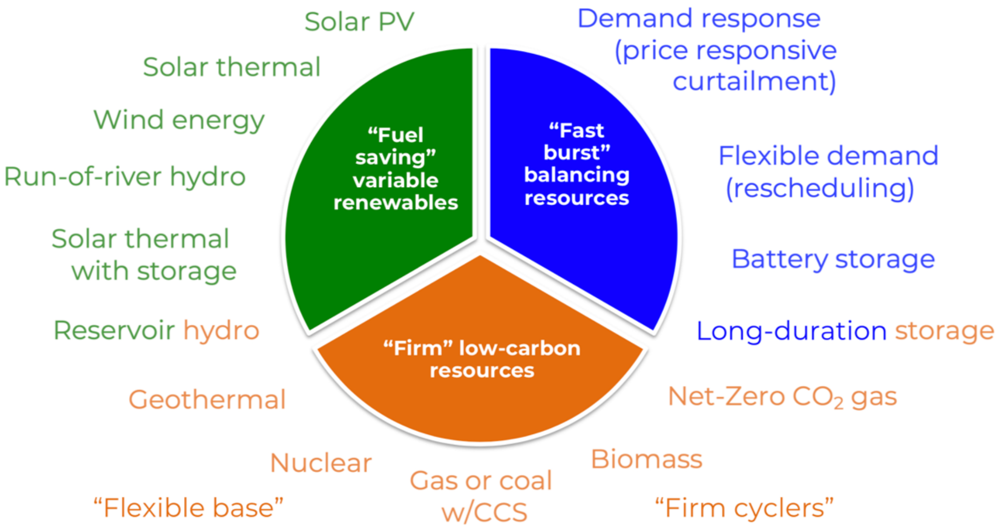


Figure 6. A taxonomy of low-carbon electricity resources. *"Firm" low-carbon resources are available on demand, any time of the year, for as long as needed, and are a critical complement to weather-dependent fuel-saving variable renewables and limited-duration "fast burst" balancing resources like batteries. Source: Sepulveda, Jenkins, de Sisternes & Lester (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," Joule 2(11). Full paper pdf at http://bit.ly/FirmLowCarbon*

The U.S. has about 950 gigawatts (GW) of firm generating capacity installed today, primarily natural gas (547 GW), coal (238 GW), and nuclear (101 GW) power plants.

Going forward, modeling for Princeton's *Net-Zero America* study finds that the U.S. needs to maintain between 500 and 1,000 GW of firm generating capacity as it transitions to net-zero greenhouse gas emissions and a 100% carbon-free electricity system.

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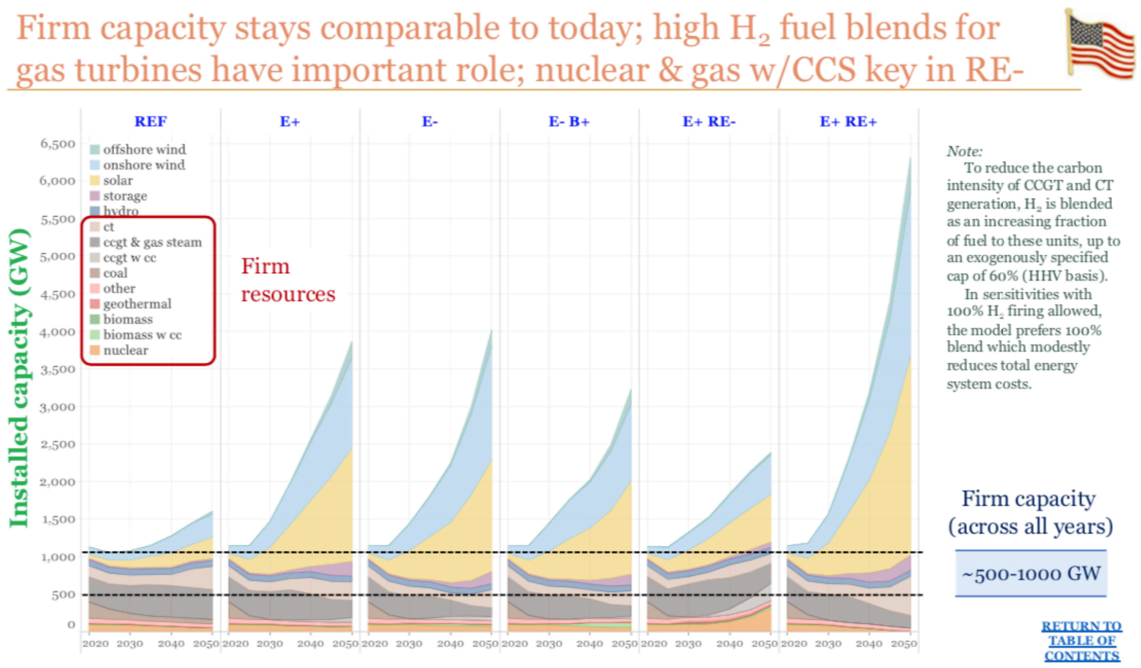
[1] Sepulveda, Jenkins, de Sisternes & Lester (2018), "The role of firm low-carbon resources in deep decarbonization of electric power systems," *Joule*. https://doi.org/10.1016/j.joule.2018.08.006



Firm capacity stays comparable to today; high H_2 fuel blends for gas turbines have important role; nuclear & gas w/CCS key in RE-

Note: To reduce the carbon intensity of CCGT and CT generation, H_2 is blended as an increasing fraction of fuel to these units, up to an exogenously specified cap of 60% (HHV basis). In sensitivities with 100% H_2 firing allowed, the model prefers 100% blend which modestly reduces total energy system costs.

Figure 7. Clean firm capacity requirements in the Princeton Net-Zero America*. Five net-zero emissions pathways for the United States and a reference case with no new policies are presented. Between 500-1000 GW of firm capacity is maintained in all cases, including a mix of combustion turbines and combined cycle power plants running on 60-100% hydrogen blend, natural gas and biomass-fired power plants with carbon capture, and nuclear power plants. This compares to about 950 GW of firm capacity in the U.S. grid today, mostly from natural gas and coal power plants. Source: Princeton Net-Zero America study.*

Over time, the U.S. therefore needs to scale-up a range of sources of clean firm power.

Clean firm resources are firm generation sources that can produce electricity with zero or near-zero emissions of greenhouse gases. This includes:

- nuclear power plants;
- coal or natural gas-fired power plants that capture and permanently store carbon emissions (carbon capture and sequestration or CCS);
- use of hydrogen or other zero-carbon fuels in combustion turbines or fuel cells;
- geothermal energy; and
- biomass power plants that capture and store carbon emissions.[2]

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[2] Some hydro dams with very large reservoirs capable of seasonal storage can substitute for firm generation. Ultra-low cost long duration energy storage technologies with storage capacity costs in the range of $1-5/kWh and with suitable power cost and efficiency combinations can also *partially* substitute for or reduce the need for firm generation capacity. See Sepulveda, Jenkins, Edington, Mallpragada & Lester, (2021), “The design space for long-duration energy storage in decarbonized power systems,” *Nature Energy* (forthcoming).

Over the next decade, ample existing natural gas capacity and existing nuclear reactors can act as firm resources and ensure reliability as wind and solar power expand and displace coal and gas-fired generation. That means that CO_2 emissions in the electricity sector can be reduced over the next decade by 70-80% by (1) phasing out coal-fired power plants; (2) maintaining existing nuclear and gas capacity; (3) reducing the total generation from natural gas power plants; and (4) increasing electricity generation from wind and solar power to roughly 50% of U.S. electricity (up from ~10% today).

Reaching 100% carbon-free or deeply decarbonized electricity systems sometime after 2030 will ultimately require some combination of (1) replacing existing fossil-fueled firm capacity with new clean firm capacity; (2) retrofitting existing fossil capacity to capture carbon emissions or (3) converting gas power plants to use zero-carbon fuels such as hydrogen.[3] New clean firm capacity will also be needed to replace any aging nuclear power plants that retire in coming years.

The time to invest in clean firm power technologies is now.

All clean firm generation technologies are all less mature and/or more costly today than is required for widespread and affordable use. This includes: small modular and advanced nuclear reactors; advanced geothermal (such as enhanced geothermal systems or closed loop geothermal); large frame combustion turbines capable of burning 60-100% hydrogen (and technologies for affordably producing hydrogen without CO_2 emissions); biomass gasification plants; Allam-Fetvedt cycle power plants; and post-combustion carbon capture systems for fossil and biomass fueled power plants.

As this Committee knows, it takes time to improve, scale-up, and drive down the cost of novel energy technologies. Wind power, solar photovoltaics, Lithium-ion batteries, LEDs, and even hydraulic fracturing all required a decade or more of proactive public policy support — including funding for R&D, demonstration projects, and the creation of early market opportunities. These efforts transformed these technologies from expensive 'alternative technologies' to affordable mainstream options. This proven process of making clean energy cheap and scalable must now be replicated for a full portfolio of clean firm generation technologies.

What is needed now is proactive investment over the next decade in R&D, first-N-of-a-kind deployments, and early market scale-up, to ensure several clean firm technologies are affordable and ready to deploy 100s of gigawatts of capacity in the 2030s and 2040s.

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[3] Alternatively, some gas-fired generating capacity could be maintained as firm capacity and used very infrequently, *if* the CO_2 emissions from these generators are offset by negative emissions technologies that permanently store CO_2 from biomass or direct air capture in geologic formations. That would make these generators net-zero emissions firm resources. Note that storage of carbon in the 'shallow' carbon cycle in the terrestrial biome (e.g. forestry or land use offsets) is not an equivalently secure form of negative emissions as geologic storage.

In the Energy Act of 2020, this Committee worked on a bipartisan basis to enact critical new authorizations to advance many of these innovative clean firm technologies, including advanced nuclear reactors, carbon capture, hydrogen, geothermal energy, and fusion technologies.

More effort and investment will be required to scale up and improve these critical clean firm technologies in the years ahead, beginning with appropriations this year to make the new authorizations in the Energy Act of 2020 a reality.

And as the Texas crisis should show us all, we must ensure that these firm resources are *actually firm*.

Firm resources are the resources we count on to be there when we need them. If they fail us – as the natural gas, coal, and even nuclear power plants did in Texas – that is when true disaster strikes.

Innovation and research should thus focus on ensuring we have adequate and *truly firm* capacity to secure a reliable, resilient, and carbon-free electricity system.

Thank you for having me today. I look forward to engaging with you on these critical issues.

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