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Climate change exacerbates electric grid resilience gaps and associated societal risks worldwide. The 2021 Texas polar vortex disaster offers many global lessons on improving resilience. Paradoxically, global warming precipitates not just heat waves, but also bitter cold fronts, paralyzing electric power generation. When an ice storm in Texas caused freeze-ups, the interdependence between intermittent fuels—such as wind and solar power—and gas and nuclear power triggered a cascading energy supply problem. Flawed political choices led to the catastrophic outcome of the crisis. After conceptualizing the gaps and risks related to the disaster, we use cross-time electricity generation mix data and comparative weather data to draw policy conclusions.

Introduction: The Resilience Dilemma

Resilience, the capacity to survive environmental crises in the age of global warming, is an international challenge. No country is exempt from the risks and damages associated with climate change and consequential storms, flooding, and fires. Analyzing a recent US case study, this article illustrates the complexity and worldwide importance of resilience. All resilience to global warming inevitably stems from local sources, but the lessons to be drawn from climate-induced crises, like the February 2021 Texas polar vortex, have global implications. Learning is a reciprocal, cross-country experience. If the United States makes mistakes but learns to strengthen subsequent resilience, other countries can also benefit from understanding the causes of electricity output failure and how to mitigate resulting societal costs.

With the exception of nuclear war, global warming is the threat to humanity with the broadest reach and the greatest potential for harm. The essential transition to non-fossil fuels is ongoing. But these intermittent fuels may also diminish the reliability and resilience of the electrical grid, destroying property

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during blackouts and threatening loss of life. This is the resilience dilemma—intermittent fuels are essential, but they also exacerbate resilience gaps.

The solution to this dilemma is to identify and minimize resilience gaps and to optimize the risk trade-offs. Fusion, hydrogen, or some yet unimagined fuel source spurred by technological innovation may someday replace contemporary energy sources of electricity output. However, until this innovation triumphs, our system relies on natural gas as an intermediary source of electricity production—a "bridge fuel." When burned in new high-efficiency plants, natural gas emits 50 percent less carbon than coal for electricity generation.[1] Natural gas, therefore, is an essential adjunct to even more efficient intermittent fuels in our increasingly warm world. Moreover, regarding multifold resilience gaps where non-fossil fuels, like solar and wind, may themselves be a cause, natural gas is an important backup. However, this backup will only be temporary; ultimately, drastically reducing carbon emissions will require reducing the use of fossil fuels, including natural gas. The only way to reduce reliance on natural gas as a bridge fuel is to systematically eliminate the resilience gaps that still plague the electrical grid during natural emergencies, such as the Texas polar vortex.

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Electric Grid Resilience Gaps: A Cascading Problem

This study seeks to understand the causes of electric grid resilience gaps and associated societal risks through the lens of the February 2021 Texas polar vortex and power outage. Electric grid resilience is the capacity of an electric grid to recover from a shock or collapse; resilience gaps are the specific problems that cause a particular grid to break down. According to a green energy consulting company, "resilience may be the hottest trending topic in the electricity sector today" amid efforts to combat global warming by use of intermittent renewable energy sources.[2] It is widely recognized that the catastrophic failure of the Texas electric grid during the February 2021 Texas polar vortex was one of the most significant and challenging events related to power systems in the last decade. Our study shows that the crisis was a cascading problem: it revealed the interdependence of energy sources; the impact of increasing reliance on intermittent energy sources in the electricity generation mix; and both risk-resilience and cost-reliability trade-offs.

First, we identify resilience gaps in the electrical grids of Texas. In the absence of capacity markets or other strategies to mitigate the disastrous impacts of massive demand surges during electricity outages, the resilience of aging electric grids weakens. As countries move to increase their renewable energy mixes and aspire to net-zero carbon emissions, increased reliance on intermittent power sources, including solar and wind, is likely to worsen these resilience gaps in the short term unless appropriate steps are taken to modernize electric grid infrastructure. The 2021 Texas electricity outage is an apt case study of why and how resilience gaps occur, and how they must be countered. Second, we reveal that challenges to resilience are becoming more frequent and more intense, especially for unprepared governments and citizens, as climate change increases the number and intensity of weather-related energy outages. Third, we examine pertinent literature on the perceived risk trade-off between the task of providing resilience to the electric power grid and other competing energy policy demands.[3,4,5,6,7,8,9] There are similar patterns of power outage risks in different locations, such as Great Britain (August 2019), continental Europe (January 2021), California (August 2020), and Texas (February 2021).[10] We categorize the various risk trade-offs at issue when addressing electricity resilience. Fourth, we examine the 2021 Texas polar vortex disaster in more detailed historical and causal terms, delineating four resilience gaps in the current grid and electricity market. Finally, in our conclusion, we analyze possible policy and industry responses to these gaps that can strengthen electricity resilience overall.

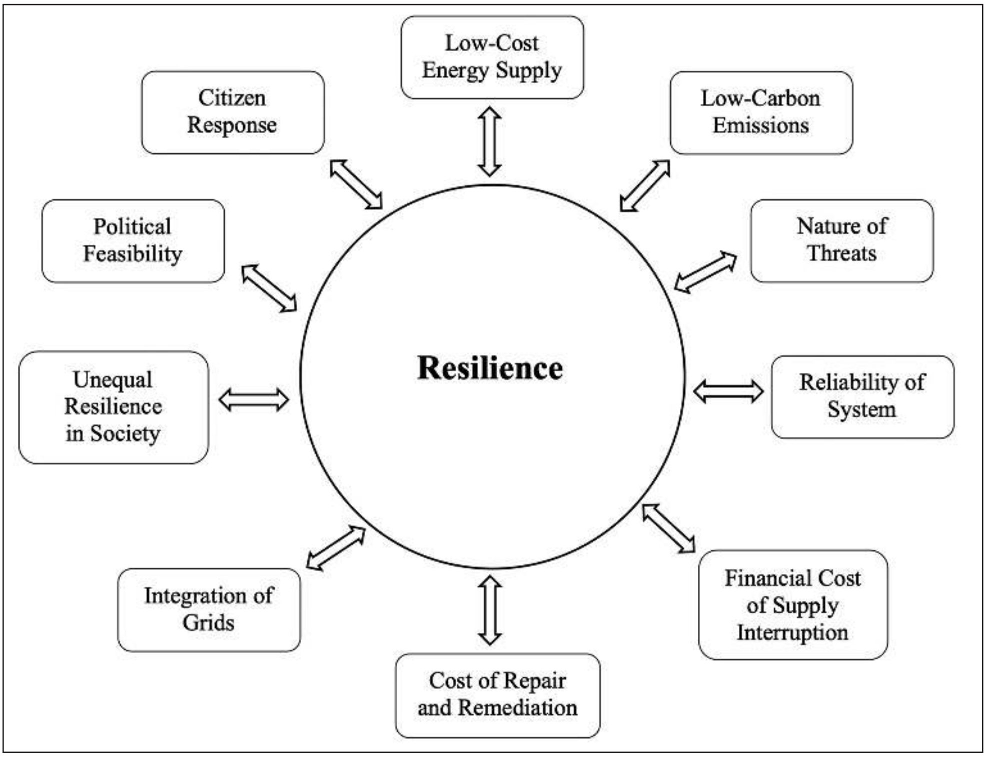
Electricity Resilience: Primary Risk Trade-offs

Resilience is defined in a number of important ways.[11] As an *attribute* of the power system, resilience is defined by three factors: prevention, recovery, and survivability.[12] As the *performance* of power systems, resilience is the ability of a system to recover from shock, stress, or abnormal negative change.[13] Another aspect of resilience is reliability of access to power where and when it is needed. According to the Federal Energy Regulatory Commission (FERC), reliable operation means "operating the elements of the Bulk-Power System within equipment and electric system thermal, voltage, and stability limits ... so that instability, uncontrolled separation, or cascading failures of such a system will not occur ..."[14] Drawing upon a conception of resilience developed at Sandia National Laboratories, a resilient electrical system is one that can "bounce back."[15]

A primary risk trade-off exists between resilience and other related, yet competing policy demands (Figure 1). In addition, a set of secondary risk trade-offs exists among all of these competing policy demands themselves. According to some analysts, "it is not possible for electricity supply to be low-cost, resilient, and low-carbon at the same time."[16] Each society must decide for itself what the optimal relationship is between resilience and each of its other competing electricity demands.[17] The polar vortex disaster clarified the decisions Texas had made regarding the optimal mix between *low-cost energy supply*, *low-carbon energy emissions*, and *resilience*. In particular, resilience seems to have lost out.

Composed of many individual electric utilities, the Texas electricity market is not controlled or dominated by a single monopoly or rate-setting governmental agency that determines price and supply. Instead, the electricity market prioritizes *low-cost energy supply* for the consumer. *Low-carbon emissions* have also become a priority in Texas—25 percent of its electricity output

Figure 1. Primary Risk Trade-offs



is provided by wind, and both nuclear and solar power fuel significant portions of supply. The trade-off between resilience and low-carbon emissions is costly; the number of outage minutes increases with the percent of electricity generation supplied by wind in current grid infrastructure.[18]

Another trade-off that Texas faces relates to the series of *natural threats* to its electricity grid. Preparation for one threat—such as summer hurricanes—may diminish the state's capacity to cope with another threat, such as winter polar vortexes. Preparation for natural threats must also not impede preparation for other threats, such as cyberterrorism.

Despite a high level of *reliability* during normal intervals of electricity supply, Texas has one great vulnerability in *capacity* to meet seasonal peak load problems—heightened demand due to short-term temperature extremes (e.g., high demand for air conditioning during summer heat waves or for heating during winter cold spells). Daily peak load issues are handled by a diverse energy supply. In contrast, seasonal peak load problems can strain the electrical grid across fuel types in cascading ways.

Texas seriously underestimated the society-wide *financial cost* of electrical supply interruption. Incorrect estimation of supply interruption costs is problematic.[19] Given the severity of the damage caused by summer hurricanes and flooding and by abrupt winter freezes each year, the costs for Texas can reach hundreds of billions of dollars per event. The human costs are even more monumental and tragic. *Costs of repair and remediation* can be broken down into two distinct categories—direct and indirect. By not acting soon enough or decisively enough, states can allow comparatively small costs to mushroom. During the 2021 polar vortex disaster, Texas came within minutes of a total shutdown of the entire electrical grid.[20]

Integration of grids theoretically would have given Texas the opportunity during the crisis to tap into surplus electricity supply elsewhere. However, the state has long resisted doing so to avoid being subjected to federal rules and regulations. For example, under such rules, even at a time of high demand among its own electricity consumers, Texas would be obligated to help other regions if they were caught in a costly emergency. In addition, these other grids might not be as market-driven as that of Texas, complicating the terms of agreement.

The costs and burdens of electricity resilience, as well as the struggle to recover from outages, may be borne unequally by poor and disadvantaged groups.[21] This study explains *resilience inequality*, measured by the duration of outages in different areas, as a product of bureaucratic decision rules. Utilities prioritize areas that provide community services, like health facilities, to the largest number of affected persons, even at the expense of low-income neighborhoods.[22] Rigid adherence to bureaucratic rules can hide these unfair practices.[23]

Not all approaches to grid resilience are *politically feasible* for a community.[24] Engineering feasibility—the possibility of producing a technical solution—is not identical to political feasibility—coordinating state bureaucracies, political representatives, and voters to support spending tax dollars on new technological fixes.[25] Texas is well known for its desire for political independence from federal control. It is also stubbornly committed to a free-market philosophy that tends to favor efficiency and cost-effectiveness over the provision of extensive social services.

Citizen response to natural disasters and consequent electrical grid outages is varied. Despite advanced warning, some citizens are unaware of or unable to take steps to safeguard themselves and their families. Perhaps this important risk trade-off could be mitigated if the architects of electrical resilience better understood the motivating and limiting factors related to citizen response to weather emergencies.

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Data Sources for Focused Analytical Assessment

We integrate the literature on risk trade-offs and resilience with a historically anchored examination of the crisis, incorporating historical electricity generation mix data from the US Department of Energy (DOE), the Energy Information Administration (EIA), the Electric Reliability Council of Texas (ERCOT), and the International Atomic Energy Agency (IAEA), as well as historical weather data from the National Oceanic and Atmospheric Administration (NOAA).

Figure 2 presents data from the EIA's Form EIA-930, "Hourly and Daily Balancing Authority Operations Report," which includes data from each electricity balancing authority in the United States. For the purposes of our analysis, Figure 2 depicts only the relevant balancing authority region and time period (i.e., the data for ERCOT hourly electricity generation by energy source for February 2021).

For context, Figure 3 presents monthly climate data (Form F-6) from NOAA's National Weather Forecast Office for the degrees Fahrenheit colder than the 30-year average in College Station, Texas to illustrate the relationship between extreme weather in Texas, the hourly electricity generation from natural gas in ERCOT, and the timing of the power outages.[26]

Figure 4 presents the EIA data (Form EIA-930) for natural gas and wind as shares of total electricity generation in ERCOT for the month of February 2021. Finally, using DOE, EIA, and ERCOT data, we examine both the absolute and relative contributions of various energy sources to the electricity generation mix, as well as the dramatic shift in the generation mix as the crisis unfolded.

Analysis, Results, and Findings

The deep freeze of February 2021 and the resulting power outages that impacted most of Texas for nearly a week killed hundreds of people. The severity of the unfolding crisis clouded and politicized interpretation, with Republicans blaming icing on wind turbines and Democrats blaming natural gas for the lack of electric power. What can we now say about the causes of the power outages, and what policy lessons can we learn regarding grid reliability and resilience?[27,28]

The Texas electricity market has been deregulated since the late 1990s, meaning that the roles traditionally provided by a regulated public utility have been unbundled, thereby separating the generation, transmission, and retail functions. The Electric Reliability Council of Texas is an independent system operator (ISO) regulated by the Public Utility Commission. It is responsible for managing electricity load in order to maintain the integrity of the electric grid covering more than 90 percent of the Texas electricity market.[29] Because ERCOT is the ISO for an intrastate (rather than an interstate) electricity market, it does not fall under the jurisdiction of FERC. This is by design. But the lack of connections to interstate power markets—for example, the neighboring fourteen-state Southwest Power Pool—also contains certain drawbacks which became apparent as the crisis unfolded and approximately four million Texans lost power during the week of February 15.

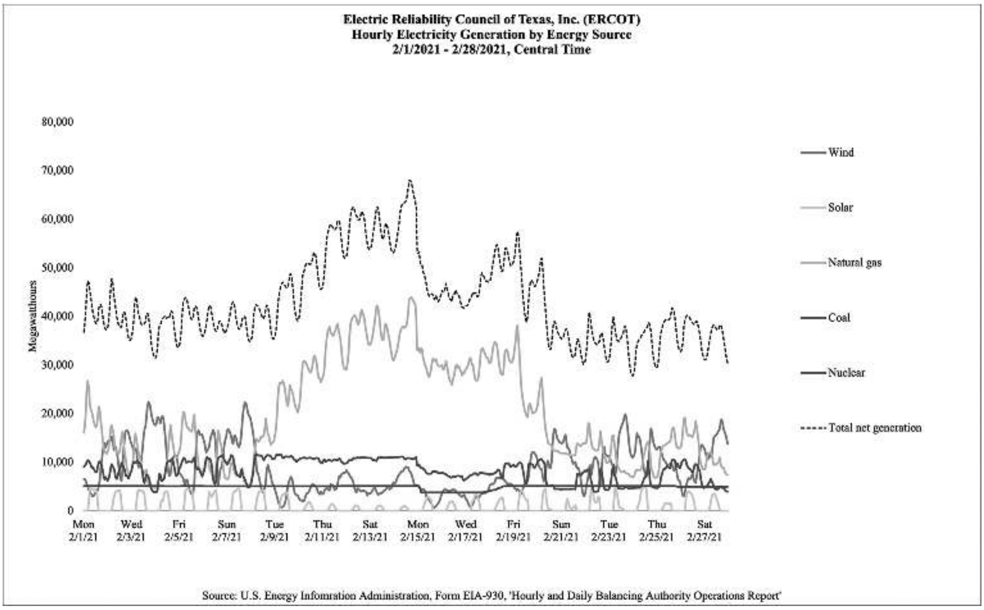
The Interdependence of Energy Sources for Electricity Generation

Politics aside, a deeper analysis reveals the interdependence of energy sources. Upon close examination of the hourly contributions of various electricity generation sources over the entire month of February (Figure 2), natural gas played a critical role in keeping the lights on during the crisis.[30] Under normal circumstances, such as the beginning and end of February, wind and solar generation follow a natural rhythm, rising and declining throughout the day, with natural gas generation picking up as wind and solar fall and declining as they rise.[31] This is to be expected since wind and solar are intermittent power sources.[32] Nuclear provides a small yet steady base of resilience, while wind represents nearly 30 percent and natural gas represents nearly 50 percent of total installed capacity.[33,34] In the month of January 2021, wind accounted for 25 percent and natural gas accounted for 35 percent of ERCOT's power generation.[35]

When the polar vortex dropped into Texas on the evening of February 14, icing on wind turbines led to a rapid decline in wind generation. By 7:00 p.m., wind generation had already fallen by 63 percent from its earlier February peak, from 22,415 megawatt hours (MWh) a week and a half earlier to only 8,261 MWh. Meanwhile, natural gas generation had risen from its prior February peak of 26,716 MWh to 43,523 MWh, an increase of 63 percent (Figure 2).[36]

This rapid decline in wind generation capacity caused the frequency on the electric grid to drop below the required 60 hertz in the early morning hours

Figure 2. Hourly Electricity Generation by Energy Source, Texas, February 2021



Source: U.S. Energy Information Administration, Form EIA-930, 'Hourly and Daily Balancing Authority Operations Report' of February 15th. In response, ERCOT declared an Energy Emergency Alert Level 3 at 1:23 a.m. local time and implemented rotating outages to preserve grid integrity at the lowest temperature reached (note the peak in the "Colder than 30-year normal" curve of Figure 3).[37] By 2:00 a.m., wind generation accounted for only 8 percent of total electricity generation, down 37 percent over five hours. At the same time, natural gas accounted for 65 percent of total power generation. But the forced outages were not well-targeted, impacting critical natural gas infrastructure that depended on access to reliable electricity, from wellheads to pipelines.[38,39] By 7:00 p.m. wind generation accounted for only 1.78 percent of power generation (Figure 2).

The next day, power cuts to natural gas infrastructure reduced natural gas generation, although it never fell below its normal peak of approximately 25,000 MWh. Even at its lowest, natural gas still accounted for 60 percent of the total power generated (Figure 4).[40]

Discussion

From a close analysis of the timing and cascading nature of the power outages during the February 2021 Texas polar vortex, what can we glean about the role of diversified sources of power generation in the Texas grid? What are the trade-offs that exist within the Texas energy market as it is currently designed?

The Impact of Increasing Reliance on Intermittent Energy Sources

As weather conditions impeded wind generation, natural gas-fired electricity generation ramped up, as expected. Installed capacity utilization of natural gas generation reached 85 percent on February 14; installed capacity utilization of wind generation reached only 30 percent before falling to a low of 2 percent during the storm.[41,42] ERCOT's public list of generator outages and derates (a decrease in the available capacity due to abnormal circumstances) during the storm demonstrates that wind generation outages and derates happened early on, exacerbating the crisis.[43] In this way, the Texas power outages were a cascading problem: wind generation outages led to power cuts to critical natural gas infrastructure, which in turn led to a loss of natural gas-fired electricity generation, causing even more power outages.[44,45]

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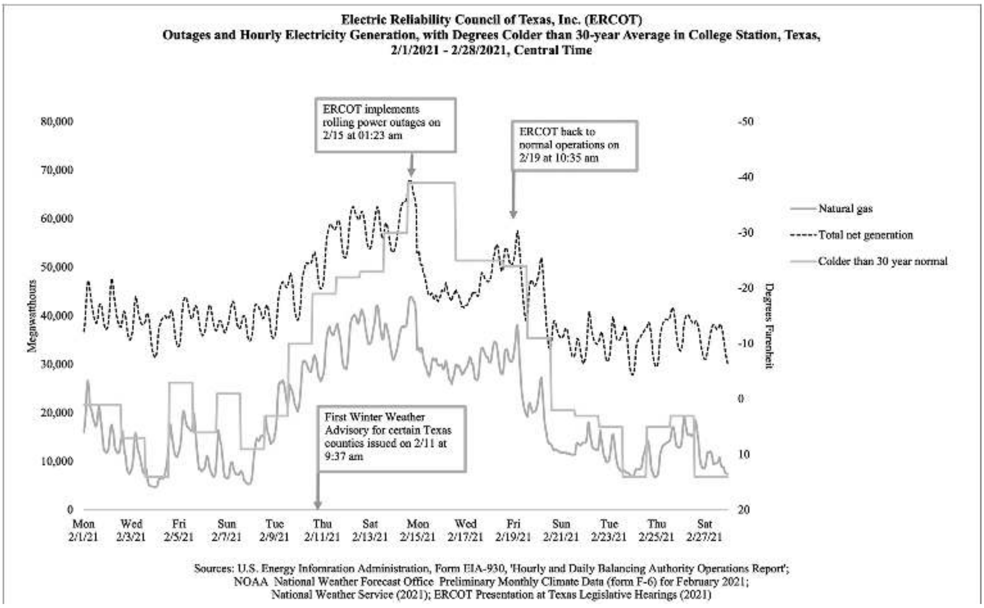
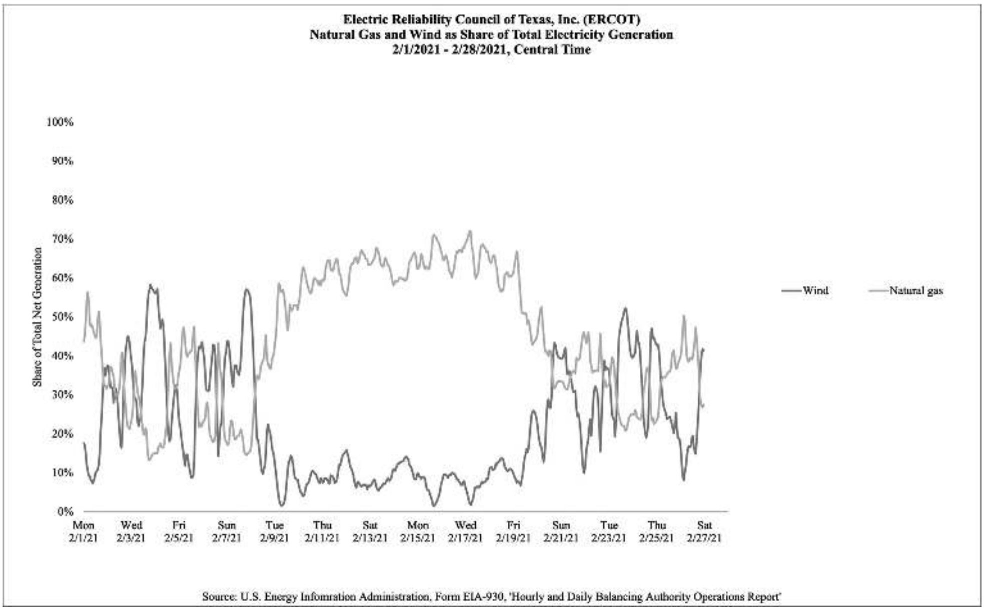
Natural gas is used in the winter for both electricity generation and home heating. In preparation for this high seasonal demand, substantial amounts of natural gas are injected into storage in the summer months, typically amounting to over 3.5 trillion cubic feet by the end of the injection season in early

Figure 3. ERCOT Outages and Hourly Electricity Generation Superimposed with Degrees Colder than 30-Year Average Temperature in College Station, Texas, February 2021



Sources: U.S. Energy Infomration Administration, Form EIA-930, 'Hourly and Daily Balancing Authority Operations Report';
NOAA National Weather Forecast Office Preliminary Monthly Climate Data (form F-6) for February 2021;
National Weather Service (2021); ERCOT Presentation at Texas Legislative Hearings (2021)

Figure 4. ERCOT Natural Gas and Wind as Share of Total Electricity Generation, February 2021



Source: U.S. Energy Infomration Administration, Form EIA-930, 'Hourly and Daily Balancing Authority Operations Report'

November. On February 14, US natural gas demand reached a new record of 148.3 billion cubic feet per day.[46] Moreover, for the week ending on February 19, natural gas withdrawals from storage in the South Central region, which includes Texas, totaled a record 156 billion cubic feet.[47] Despite a temporary decrease in wellhead production due to "freeze-offs" and power cuts to natural gas infrastructure, and despite a spike in spot market prices during the storm, the region's storage of natural gas averted any physical shortage.[48]

As the events of mid-February make clear, extensive reliance on wind increases the importance of power supply diversification across a wide geographic area in order to mitigate the potential consequences of wind's intermittent nature.[49,50] By comparison, the Southwest Power Pool, which also relies on wind for approximately 30 percent of its electricity generation and faced even colder temperatures than Texas, could draw power from a fourteen-state area and did not face a severe crisis.[51,52]

Trade-offs in Electricity Market Design

When no one is responsible for resilience, no one will take on the responsibility, and when no one is compensated for providing resilience, no one will provide it.

ERCOT's "energy-only" market design met Mother Nature and came up short, once again.[53] Unlike other deregulated electricity markets, the Texan system has no capacity market, which means that no one is rewarded for maintaining spare capacity. Power generators are paid only for the electricity they provide to the market.[54] When no one is responsible for resilience, no one will take on the responsibility, and when no one is compensated for providing resilience, no one will provide it. As we saw in February 2021, if there is no additional electricity supply, simply allowing the price to rise to ERCOT's maximum of $9,000 per megawatt hour cannot increase supply.[55] This is the problem inherent in an energy-only market for electricity.

Given the mild temperatures of typical Texas winters, the "winterization" of energy infrastructure in the state had not been as high a priority as it was in colder parts of the country.[56] (Winterization is the physical protection of energy generation and storage equipment from extreme temperatures and icing with insulating materials and other techniques to improve power generation during winter emergencies.) However, contrary to popular belief, the storm was not "unprecedented"—similar winter weather has occurred in 1983, 1989, and most recently in 2011.[57,58] In fact, the power outages resulting from the February 2011 storm prompted a recommendation from FERC and the North American Electric Reliability Corporation (NERC) to winterize equipment.[59] To be sure, the costs and benefits of winterization must be weighed against the need to ensure that power generation and grid infrastructure can withstand the high temperatures of a typical Texas summer.[60] Nevertheless, climate change is likely to cause more extreme weather events, like strong summer hurricanes and winter polar vortexes dipping further south.[61] Power outages due to hurricanes, such as Hurricane Harvey in 2017, have also been a problem. But the nature of the problem is different in the summer, when winterization is not an issue. Whereas in the winter natural gas is used for both heating and electricity generation, in the summer there is very little heating demand, especially in Texas.[62] This trade-off between preparing energy systems for winter weather emergencies and summer extreme heat emergencies further complicates policy decision-making about how, where, and when to fund technological “fixes” to these season-specific, short-term energy emergencies.[63]

In addition, there are trade-offs between risk and resilience and between cost and reliability.[64,65] The electricity market in Texas, as it is currently designed, prioritizes low costs for consumers over long-term investments in reliability. Whether this is a feature or a bug is a matter ultimately up to the people of Texas to decide. But it is important to note that retail competition in an unbundled, energy-only electricity market involves an implicit, largely unseen transfer of risk to the consumer. This transfer had been masked by generally low prices, but it has now been made explicit in the form of widespread power outages and, for those who still had power, crushing electricity bills.[66]

Finally, we must return our attention to the centrality of the political trade-offs highlighted at the beginning of this article. As memories of the latest winter storm fade, and as Texans weigh the trade-offs between risk and resilience and cost versus reliability, they are for political and cultural reasons unlikely to fundamentally change their collective willingness to pay for more reliability so as to reduce risk and reap higher rewards.[67]

Electric Grid Resilience Gaps: In Search of Policy Strategies

Where are the electrical grid’s weakest links? In advance of a crisis, we must be able to pinpoint each potential cause of a system’s failure. In addition to the trade-offs just discussed and the larger-scale risk trade-offs delineated in the introduction, Texas must bridge certain resilience gaps to manage future electricity supply crises. At least four resilience gaps can be identified in the 2021 Texas power outage and are indicative of future problems.

Resilience Gap #1: Vulnerability of the Overall Process of Energy Substitution Depending on Energy Type

Unless otherwise offset, the substitution of an intermittent fuel, such as wind or solar, with a more continuously supplied fuel, such as natural gas or nuclear energy, during a natural disaster is likely to reveal resilience gaps that shut down the system. In the coming decades, massive substitution of non-fossil fuels for fossil fuels will take place worldwide. As a result, experts predict an increase in the number and severity of resilience gaps associated with electricity grids.

Which natural events have a high probability of reoccurring? For example, when will another polar vortex hit Texas? Where are resilience gaps in each type of electricity grid likely to appear next? A worldwide, country-by-country inventory of likely failures must be compiled starting with the United States itself.

Resilience Gap #2: As Demand Surges, Market-based Systems Falter When Supply Fails to Meet Demand

Who assumes the risk of grid failure—the consumer, the utility, or the government? Who pays to offset that risk, and how? Just the prospect of raising electricity rates to phenomenal levels in times of crisis does not ensure that a utility will itself assume the cost of spare capacity, especially if the carrying cost of that capacity is high and the duration of actual use is minimal. This is the situation in which Texas found itself.

On the other hand, if utilities are required to assume the cost of extra capacity, or if the government assumes that cost directly, efficiency may not be as high. In other words, the cost of increasing resilience may be excessive and wasteful.

Nevertheless, a society facing a high likelihood of future demand surges during electricity outages must decide how to eliminate resilience gaps and how to pay for this offset to the risk and cost of inevitable future outages.[68] A market-based system may be efficient, but there is no guarantee that it is also resilient.

Resilience Gap #3: Freeze-ups on Energy Production Equipment

The Texas polar vortex is sometimes described as a deep cold spell. While the event did involve a deep cold spell, that description does not recognize the nature of the accompanying resilience gap. An important element of the resilience gap was that the cold spell involved an ice storm. It was the ice storm that caused energy equipment to freeze, from natural gas wellheads to pumps to wind turbine blades. A field study has indicated that icing on wind turbines reduces their power production by up to 80 percent of normal output.[69] This was borne out in the February 2021 crisis, as recognized in the final report by FERC and NERC.[70] The ice storm, not the cold front per se, caused electricity output to plunge to unacceptably low levels.

Resilience Gap #4: Natural Gas Transmission Uses Electricity, Too

A precise analysis of the Texas resilience gap involves identifying the reason natural gas supply eventually faltered, halting much of the electricity output. Although some natural gas wellheads froze, the bulk of the natural gas used to fuel electric utilities came from large underground storage caverns, not from the wellheads directly. Transmission of natural gas from these storage facilities was the primary source of the problem. Compressors and pumps convey natural gas from storage facilities to electric utilities. Since the natural gas compressors use electricity to operate, a shortage of electricity led to the stoppage of natural gas transmission, which in turn caused a further diminution in power output. Thus, a cascading series of constraints, not a single cause, eventually brought the entire system to near collapse.

Policy Strategies

Based on the above analysis, we conclude that the four energy grid resilience gaps together suggest pathways to increasing overall energy resilience. Managers worldwide may draw similar conclusions regarding their own electricity grids and populations.

Policy Strategy Addressing Resilience Gaps #1 and #2: Redesign ERCOT to Add a Capacity Market

Capacity markets provide electricity where peak load problems exist or where a surge of demand caused by a crisis threatens a system collapse.[71,72] Capacity markets parallel normal electricity markets, but someone must pay for this reserve capacity. Surplus capacity is expensive because it is relied upon so infrequently and may remain unused by consumers for long periods of time.

Nevertheless, market failures create the need for capacity markets. Customers often do not know the true price of electricity, and price signals may sometimes fail. In consequence, customers cannot adjust their demand quickly and appropriately in response to price realities. Electricity demand during crisis intervals is highly price inelastic. A capacity market would help correct these electricity market failures, thus enabling Texas to improve its otherwise efficient market.

Policy Strategy Addressing Resilience Gaps #2, #3, and #4: Join ERCOT to the Southwest Power Pool

Although the Southwest Power Pool is not the largest alternative electricity grid, it is the most geographically proximate to Texas and likely the most similar in terms of cultural and political thought. However, an integration scheme may contain legal clauses, conditions, or circumstances to safeguard the electric grid that would cause the agreement to collapse in an hour of greatest need.[73] These risks would need to be addressed by regulators, legislators, and relevant industry experts alike.

Policy Strategy Addressing Resilience Gaps #1 and #3: Invest in Research and Development to Lower the Cost of Winterization and Weatherization of Energy Equipment and to Improve Battery Storage

Improved battery storage technology can eliminate resilience gaps by safeguarding the operation of compressors and pumps that transmit natural gas from storage facilities to utilities. In fact, the US federal government—in particular, the Department of Energy (DOE)—is currently investing in novel materials and technologies to improve energy storage. For example, the DOE's Basic Energy Science Pro-

> *Improved battery storage technology can eliminate resilience gaps by safeguarding the operation of compressors and pumps that transmit natural gas from storage facilities to utilities.*

gram supports energy innovation hubs, like the Joint Center for Energy Storage Research and the Molecular Foundry at Berkeley, that research the multifold aspects of energy production and storage.[74]

Conclusion

A recent *Science* article written by the climatologist Judah Cohen and his colleagues at the Massachusetts Institute of Technology has re-introduced resilience into the mainstream of policy discussion. The article demonstrates that the Texas polar vortex and other "stretching events" involving abrupt, intense winter cold are not random. They are linked to the atmospheric turbulence above the Arctic created by global warming. Warming is twice as rapid in the Arctic as it is elsewhere. Since 1979, the increased number and severity of stretching events has increased the likelihood of sharp winter cold spells.[75]

The paradox is that global warming is linked to severe winter freezes. This counter-intuitive proposition that the heating of the earth's atmosphere can also cause massive winter temperature drops has now received strong empirical support. Cold Arctic air is normally trapped at high altitudes as it circles the globe. Cohen and his colleagues have shown causally how and why this encapsulated cold air periodically spills out over southern regions. As global warming persists, these cold spells will likely become more common not only in the American Southwest, but also worldwide. Events like the Texas polar vortex can no longer be dismissed as irregular but unlikely occurrences. On the contrary, "deep freezes" may become much more common than historically experienced. Utilities and governments must now work more earnestly to address the resilience gaps that exacerbate the impact of sudden massive cold fronts.

The more effectively that large electric grid resilience gaps are addressed, and the more successfully that risk trade-offs are optimized, the more manageable the task of responding to and recovering from climate-induced energy crises.

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