Enhancing the reliability of bulk power systems against the threat of extreme weather: lessons from the 2021 Texas electricity crisis

Chiara Lo Prete and Seth Blumsack

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Abstract

The February 2021 cold weather outages in Texas remain a subject of important investigation, and lessons learned from the crisis have broader relevance for bulk power systems around the world. This article focuses on the policy responses to what we view as the root causes of the extended blackouts: the insufficient preparation of electric generating units and natural gas infrastructure for the winter storm, and the inability of natural gas supply to meet demand for residential heating and electricity generation. Measures to reduce the risk of power interruptions during extreme weather events should not be limited to hardening existing infrastructure. We discuss three additional systems-level strategies to prevent and mitigate the adverse consequences of extreme weather events: improving generation resource adequacy and planning in the electric power sector; promoting demand-side tools, such as dynamic pricing options that do not expose residential customers to bill volatility; and implementing market and planning reforms that recognize critical infrastructure interdependencies. The response in Texas so far has considered weatherization requirements for electric generators and critical natural gas facilities, and mapping of critical infrastructure sources in the electricity supply chain. However, enhancing grid reliability against the threat of extreme weather will require more systems-level reforms.

Keywords: Texas, ERCOT, resource adequacy, reliability, electricity, market design.

1. Introduction

In February 2021, Texas experienced a 1-in-30-year cold weather event that resulted in sub-freezing temperatures well below average for over six days (Doss-Gollin et al. 2021). Given the state's reliance on electric heating (Davis 2021), the extreme cold weather drove winter electricity demand to unprecedented levels: around 7pm on February 14 load rose to over 69 GW, 3 GW higher than the previous winter record in 2018 (ERCOT 2021a; Baldick 2021). Meanwhile, electricity supply fell significantly: about 32% of installed generation capacity was already offline by 1:20am on February 15, when the grid operator managing about 90% of the state's electric load, the Electric Reliability Council of Texas (ERCOT), was forced to initiate customer load-shedding (ERCOT 2021a). More than 10 million people in Texas lost electric distribution service (Busby et al. 2021), and a large swath of electricity customers in ERCOT were without power for up to 96 hours. At least 210 people died during the event, and losses to the Texas economy were estimated between $80 and $130 billion (Federal Energy Regulatory Commission, North American Electric Reliability Corporation, and Regional Entities 2021).

The event was followed by extensive finger-pointing, and some immediate reactions blamed competition, ERCOT's market structure and grid management, wind's underperformance and limited connectivity with neighboring states. Former regulators and economists analyzed factors contributing to the crisis and proposed remedies (Aagard and Kleit 2021; Busby et al. 2021; Cramton 2022; Hogan 2021; Joskow 2021; Littlechild and Kiesling 2021; Michot Foss, Wood, and Perlman 2021; Palmer and Cleary 2021; King et al. 2021; Wood et al. 2021). Most papers agree that the root causes of the crisis were the insufficient preparation of electric generating units and natural gas infrastructure for the winter storm, and the inability of natural gas supply to meet demand for residential heating and electricity generation. In contrast, the range of proposed remedies is wider and includes mandatory winterization (Busby et al. 2021; Wood et al. 2021), revisions of the scarcity pricing framework (Littlechild and Kiesling 2021), improved communications (Busby et al. 2021; Cramton 2022), and expanded interstate interconnections (Busby et al. 2021), among others. In November 2021, the Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC) issued a comprehensive report providing further insights into the primary sources of the extended blackouts, and making key recommendations to prevent recurrence of the event (Federal Energy Regulatory Commission, North American Electric Reliability Corporation, and Regional Entities 2021).

As of the time of writing, the response in Texas has considered weatherization requirements for electric generators and critical natural gas facilities, and mapping of critical infrastructure sources in the electricity supply chain. By and large, however, reforms in Texas and elsewhere have not addressed fundamental systems-level practices to enhance the reliability of bulk, i.e., transmission-scale, power systems against the threats of extreme weather. We contribute to the literature on the Texas electricity crisis by discussing these types of strategies through policy recommendations around power generation planning, the demand side of the electricity market, and interdependence of multiple critical infrastructures. We discuss each strategy reviewing relevant failures in the ERCOT system and the policy response to the crisis in Texas, drawing comparisons with other systems, and weaving insights from past studies into the analysis.

2. *Recommendation 1*: Improve generation resource adequacy and planning in the electric power sector

Resource adequacy is foundational for providing reliable electric service,[1] and means "having sufficient resources to provide customers with a continuous supply of electricity at the proper voltage and frequency, virtually all of the time", recognizing scheduled and reasonably expected unscheduled outages of equipment (North American Reliability Corporation 2013). Resources include the electric power generation and transmission facilities that produce and deliver electricity, as well as programs that reduce electricity demand. System operators manage the grid with the reliability goal of "keeping the lights on," and are involved in resource adequacy and planning. In Texas, ERCOT manages the electric power grid serving more than 26 million end-use customers (about 90% of the state's electricity demand), runs wholesale electricity markets and administers the process of customer switching from an electric utility or retail electric supplier to another in competitive choice areas. ERCOT also conducts studies, develops forecasts and publishes reports to assess resource adequacy in its footprint. Among these analyses, the Seasonal Assessments of Resource Adequacy (SARA) reports examine the impacts of factors that may affect the performance of resources to meet peak electrical demand in the short term.

Seasonal adequacy analyses conducted by ERCOT and their underlying forecasting models failed to predict the severity of the "polar vortex" in February 2021, leading to underestimation of electricity demand and overestimation of electricity supply. On the demand side, ERCOT's most extreme winter resource adequacy analysis (the "Extreme Peak Load/Extreme Generation Outages During Peak Load" SARA scenario for Winter 2020-21) assumed a peak electricity demand of 67,208 MW (ERCOT 2020). Absent load shed, it is estimated that peak demand during the crisis would have been 76,819 MW (ERCOT 2021a), i.e., about 9,600 MW (or 14%) higher than the forecast in ERCOT's most extreme winter scenario. On the supply side, ERCOT's worst-case scenario assumed 4,074 MW of planned generator outages, 9,879 MW of forced outages, and no downward adjustments for wind output (ERCOT 2020). At the time of peak demand and highest deficit in reserves, planned outages were about 900 MW higher than assumed by ERCOT, forced outages of thermal generation were over 2.5 times higher, and wind output was 2,830 MW lower than expected (King et al. 2021). Importantly, the seasonal assessment for Winter 2020-21 did not consider the possibility that adverse conditions might affect demand *and* supply simultaneously, as in February 2021.[2]

The Texas crisis illustrates the need to improve both short-term and long-term resource adequacy and planning processes in the electric power sector. Three improvements in particular are relevant for areas where power grids may experience weather-induced stresses. First, current approaches normally assume that each generator in a power system fails and recovers independently of other generators, and do not consider common mode failures, such as the loss of multiple units

[1] NERC defines a reliable bulk power system "as one that is able to meet the electricity needs of end-use customers even when unexpected equipment failures or other factors reduce the amount of available electricity" (North American Electric Reliability Corporation 2013).
[2] For example, the "high demand-low wind output" and "high demand-low thermal output" were treated as separate extreme case seasonal scenarios. Since Summer 2021, ERCOT's short-term adequacy assessments include multiple adverse condition scenarios.

due to frozen equipment or cooling water constraints. As a result, the electric industry tends to understate the probability of supply disruptions affecting multiple generating units at the same time (i.e., overstates reliability). More accurate assessments of resource adequacy would account for correlations in generators' outputs and their combined probability of being available. Similar methods are already employed to calculate the Effective Load Carrying Capability (ELCC) of renewable resources.

Second, resource adequacy assessments typically use seasonal ratings of renewable energy resources, which are based on expected generation but differ from actual availability. This may create challenges in maintaining system reliability due to unexpected and potentially large variations in the output of dispatchable units that are required to maintain system balance, but may be offline due to common cause failures. To illustrate, in its SARA report for Winter 2020-21, ERCOT assumed that it could count on an average winter-rated capacity contribution of 6,142 MW from existing wind projects (plus 928 MW from planned projects), while 1,791 MW would be available in an "Extreme Low Wind Output" scenario (ERCOT 2020). Using data from the U.S. Energy Information Administration (2022b), we analyzed hourly electricity generation by fuel source in ERCOT between 7pm on February 14, 2021 (i.e., when the system hit a winter peak demand record of 69 GW) and 11pm on February 19, 2021 (i.e., when the grid operator declared return to normal operations). During this critical time, wind output was below the expected low wind output level of 1,791 MW 11% of the time. Further, hourly wind availability ranged from 2% to 38% at a time of widespread failure of thermal generation capacity. While the variability of wind generation did not play a significant causal role in the Texas crisis, the combination of thermal output unavailability with low and highly variable wind output during the event illustrates the greater challenge to maintaining grid reliability. How planning methods and metrics should evolve to better capture the stochasticity of variable resources remains an open question. A recent report by the Electric Power Research Institute (2021) calls for the application of stochastic mathematical programming models for resource planning and the development of probabilistic metrics that capture the risk of economic loss to the consumers. However, stochastic methods and metrics currently face computational and parametrization challenges that constrain their applicability in real-world systems, and communicating the range of risks and potential outcomes to decision makers may be complex. On the other hand, broader scenario analysis in a deterministic modeling framework would enhance understanding of potential threats to which electric power system may be exposed, without requiring fundamental changes to current practice.

Third, resource planning typically relies on historical meteorology despite its increasingly poor representation of the future. For example, the low wind output scenarios in the SARA reports discussed above corresponded to the 5th percentile of hourly wind capacity factors associated with the 100 highest net load hours for the 2015/16-2019/20 winter peak load seasons (ERCOT 2020). Planning future power systems based on historical meteorological data may not capture the range of conditions against which the systems must be resilient. In contrast, incorporating climate change projections into models applied to planning and operating decisions would improve understanding of potential impacts of extreme weather events on bulk power systems. Several disconnects between energy and climate modeling communities currently hinder usage of climate information in energy system models (Craig et al. 2022). However, system operators around the world are improving methods to assess the potential impacts of climate change on planning and operations: for example, as discussed in another article of the symposium, the European Network of Transmission System Operators for Electricity (ENTSO-E) integrated climate change impacts on temperatures and electricity demand scenarios in one of its major long-term planning studies (ACER 2020). The Texas Legislature took a first step in this direction by requiring Texas agencies to consider weather data by the state climatologist in determining appropriate weatherization methods for gas supply chains or gas pipeline facilities (Railroad Commission of Texas 2022). Wood et al. (2021) argue that legislation should take bolder steps to acknowledge extreme weather threats, such as mandating the use of "forward-looking 30-year climate and extreme weather predictions in combination with the worst past extreme weather and grid disaster events over a 50-year history in all planning scenarios."

Could Texas have prevented a crisis of this scale by relying on a different wholesale electricity market structure for generation resource adequacy? Some observers argued that the problems affecting ERCOT's system stem directly from the lack of a centralized capacity market that imposes penalties for not being available under scarcity conditions, as in ISO New England and PJM (Sioshansi 2021). Unlike some other organized markets in the U.S., Texas relies on an "energy-only" market in which prices for both energy and ancillary services rise above the offer prices of generation units when reserve margins are low. Prices in times of scarcity are based on an operating reserve demand curve (ORDC) that reflects the system operator's demand for reserves (Hogan 2005). This mechanism supports new generation investment and provides incentives for performance of generation capacity under a wide variety of weather conditions (Potomac Economics 2021). However, critics contend that ERCOT's "energy-only" market design and scarcity pricing complicated the task of maintaining grid reliability under grid emergency conditions (Borreson 2022).

In the aftermath of the crisis, the Texas Legislature directed the Public Utility Commission of Texas (PUCT) to make changes to the ERCOT market to rectify deficiencies identified during the event. For example, the high system-wide offer cap was lowered to $5,000/MWh to bring generation units online earlier under scarcity conditions, and non-performance penalties are under consideration (Public Utility Commission of Texas 2021). Further, in January 2023 the PUCT unanimously approved a performance credit mechanism requiring electricity suppliers to purchase dispatchable power services as insurance (Foxhall and Ford 2023). While these measures may enhance system reliability, it is worth emphasizing that the electricity shortages in Texas resulted not from a lack of generation capacity, but from a lack of *available* capacity that could produce electricity when it was needed. Between February 8 and 20, 2021, 75% of outages, derates and failures to start in ERCOT were caused by freezing issues (44.2%) or fuel issues (31.4%, mostly due to natural gas fuel supply issues) (Federal Energy Regulatory Commission, North American Electric Reliability Corporation, and Regional Entities 2021). An important question is why most generating units in Texas had inadequate winterization plans despite prior recommendations and/or did not invest in additional fuel arrangements to reduce the risk of shortages. The misalignment between social welfare maximization and the objectives of private parties (e.g., profit maximization) may result in a market failure to incent efficient outcomes. Specifically, the current electricity market design may not provide sufficient incentives for generation owners to incur the up-front costs of making fuel arrangements that would reduce the risk of shortages: when the likelihood of such events is low, incurring these costs will result in a loss most of the time, although it would be beneficial from society's standpoint to reduce reliability risks. Performance incentives (such as scarcity pricing) and non-performance penalties mitigate the problem, but do not fully solve it.[3] While the underlying market failure raises concerns, our view is that the major causes of the Texas energy crisis were not due to wholesale electricity market design, but to problems in planning and awareness of system interdependencies. Further, it is well understood that markets can fail to prepare us for extreme events that are difficult to predict and may have catastrophic impacts (Kousky and Cooke 2009; Fabra, Motta and Peitz 2022). This suggests that exclusive reliance on market mechanisms to ensure grid resilience is unlikely to work, and regulation and standards will play an important role to cope with tail events in resource planning. For example, mandating winterization may be more effective than leaving the relative investment decision to individual market participants. After the crisis, Senate Bill (SB) 3 directed the PUCT to mandate weatherization to minimum standards for power generators, with compliance requirements and penalties for non-performance. Further, the joint FERC-NERC report on the February 2021 cold weather outages recommended that the NERC Reliability Standards be revised to require generator owners to identify and protect cold-weather-critical components, retrofit existing units to operate based on extreme temperatures, and perform annual training on winterization plans (Federal Energy Regulatory Commission, North American Electric Reliability Corporation, and Regional Entities 2021).

3. *Recommendation 2*: Promote energy efficiency, customer-side curtailment and price responsive demand beyond existing programs

Section 2 focuses on supply-side solutions to address reliability challenges in the electric power sector under extreme weather and growing system variability. A complementary approach is given by the expansion of energy efficiency (EE) and demand response (DR) programs. As previously noted, the record spell and extended period of wintry weather in February 2021 drove electric demand in Texas almost 15% above the forecast in the most extreme winter scenario. About 40% of the total electric demand was for heating (Wood et al. 2021). This relatively high share is due to two factors: first, over 60% of Texas homes rely on electricity rather than gas for heating (Webber 2021); second, much of the state's housing stock was built before the adoption of building codes with insulation requirements in 2001, but uninsulated homes cannot be heated effectively at low temperatures like those experienced during Winter Storm Uri (Wood et al. 2021).

EE programs reduce the amount of power needed to provide the same services as less efficient conventional technologies. Cost-effective energy efficiency measures could reduce winter (and summer) peak electricity demand in Texas. For example, the Electric Power Research Institute (2017) estimates that Texas has a large amount of electric energy efficiency potential, which could be utilized to reduce total electricity sales by 17% and residential electricity use by 18.5% by 2030. Wood et al. (2021) suggest that better insulation and energy-efficient heaters could have reduced electricity demand by at least 15 GW during the Texas crisis (i.e., about 50% of outages and derates for thermal power plants on February 15 and 16). Increasing energy efficiency retrofits for low-income and multi-family housing across the state is especially critical, since these homes are less

[3] Since current non-performance penalties in other U.S. RTOs and ISOs are set at lower levels than the high system-wide offer cap in ERCOT at the time of the crisis ($9,000/MWh), it is unclear that capacity markets would have provided better incentives for power suppliers to perform in providing needed services, relative to an "energy-only" design (Palmer and Cleary 2021; Aagard and Kleit 2022).

energy-efficient and only a few thousand households per year receive energy efficiency improvements through federal funds. It is worth noting that engineering estimates (like the EPRI results) may overstate savings or understate the costs consumers face (Burlig et al. 2020).[4]

DR programs reduce electricity consumption at specified times, typically in response to specific calls from the system operator or price signals. They can be categorized as incentive-based programs or price-based programs (Yan et al. 2018; Federal Energy Regulatory Commission 2021). Incentive-based programs include direct load control (under which equipment like air conditioners and water heaters are remotely or manually controlled, in exchange for incentive payments and potential penalties for not responding to notices), emergency demand response (under which customers receive incentives for voluntarily reducing load during special events) and ancillary service market programs. Under price-based (or dynamic pricing) programs, retail tariffs that reflect the time-varying cost of electricity modify the timing and level of electricity consumption. These range from time-of-use (TOU) rates where prices vary at pre-set levels during the day, to critical peak pricing (CPP) that imposes much higher prices on pre-announced days in which supply is tight, to real-time prices that vary by hour and reflect changes in wholesale electricity prices.

Incentive-based demand response programs in Texas mainly target commercial and industrial customers, and few programs exist for residential customers. An example is given by the central air conditioner demand response programs offered by Austin Energy and San Antonio's CPS Energy, which cycle residential air conditioners during peak demand periods or use a smart thermostat to raise the setpoint during this period (Nadel, Gerbode and Amann 2021). Consumers receive a discount on the thermostat or a monthly payment/credit during summer months. CPS Energy also offers direct load control (often called managed charging) programs that control participants' electric vehicle charger and may reduce its power draw, if needed (CPS Energy 2022). An attractive option during severe peak events driven by temperature extremes is given by water heater demand response programs that temporarily reduce hot water temperature by shifting or curtailing energy use of water heaters through a control device. Utilities have used controllable hot water heater programs for decades as a demand side management mechanism, sometimes coupled with time-of-use rates (Goh and Apt 2004). More recently, and following the wider deployment of advanced distribution system infrastructure over the past decade, U.S. firms have been using more sophisticated load management systems that can leverage the ability of some flexible end-use devices (like hot water heaters and pool pumps) to respond to price-based or system-based signals to turn on and off (Meyn et al. 2015; Almassalkhi, Frolik and Hines 2017). These programs could be scaled up in Texas to reduce system demand during periods of stress. To illustrate, in 2020 5.43 million housing units in Texas had electric water heaters (U.S. Energy Information Administration 2022j). If *all* households participated in a water heater demand response program, and assuming an average peak reduction of 0.54 kW per participant (Nadel, Gerbode, and Amann 2021) and T&D losses of 5% (U.S. Energy

[4] The economics literature using standard panel fixed effects approaches (Allcott and Greenstone 2017; Fowlie, Greenstone and Wolfram 2018) and quasi-experimental methods (Davis, Fuchs and Gertler 2014; Levinson 2016; Myers 2020) finds that energy efficiency upgrades in residential settings deliver between 25% and 58% of ex ante expected savings. However, two recent empirical studies estimate delivered savings that are in line with engineering estimates when upgrades are implemented according to program rules (Blonz 2019) or machine learning is used to inform the empirical specification choice (Burlig et al.2020).

Information Administration 2022c), peak load could be reduced by 3,079 MW (i.e., about 10% of outages and derates for thermal power plants on February 15 and 16).

During Winter Storm Uri, ERCOT instituted voluntary load reductions through the Emergency Service Response (ERS) program, under which qualified loads and generators reduce their purchases from the grid on 10- to 30-minute notice in an electric grid emergency. The program achieved its targeted level of 1,100 MW on February 15: ERS loads exceeded their obligations, while ERS generators generally underperformed (King et al. 2021). In addition, load resources voluntarily reduced load through participation in the ERCOT ancillary services markets. In particular, Responsive Reserve Services (RRS) is a type of operating reserve that may be provided by load resources equipped with under-frequency relays curtailing load when frequency drops below 59.7 Hz. A study by the University of Texas at Austin Energy Institute found that maximum load reductions from load resources providing RRS were over 1,400 MW on February 15, 16 and 17 (King et al. 2021). In addition to actions undertaken by ERCOT, load-serving entities like CPS Energy and Austin Energy attempted to deploy their demand response programs, but the load reduction that can be attributed to these actions is not publicly known. While incentive-based demand response programs contributed to achieving a large demand reduction during the February event (over 32 GW at peak on February 16), involuntary load reduction accounted for the majority of load shed, limiting the ability of customers to respond to price signals.

Dynamic pricing programs in the U.S. have mostly targeted commercial and industrial customers, and adoption at the residential level has been slow. Few customers in Texas (and elsewhere) pay rates that vary in real time, while most face fixed rates that don't respond to market conditions. However, real-time pricing garnered national attention during the Texas crisis because about 29,000 residential customers of retail electric provider Griddy were exposed to wholesale market prices, which increased to $9,000/MWh (or $9/kWh, relative to an average wholesale price of about 2.2 cents/kWh in 2020 (Palmer and Cleary 2021)) and stayed at that level for 87.5 hours due to the problematic regulatory implementation of the scarcity pricing mechanism (Littlechild and Kiesling 2021). Texas' retail choice design did not mandate load hedging for residential customers, and some customers may not have understood the risks and uncertainties associated with plans offering an unhedged wholesale-indexed product. The decision of the PUCT to keep wholesale market prices at emergency levels for an extended period exacerbated the risks faced by unhedged retail customers. Financial consequences were devastating for residential customers, and several companies (including Griddy) that inadequately hedged price risk declared bankruptcy after the crisis subsided.

It is unlikely that dynamic pricing alone could have balanced supply and demand during the Texas crisis. While the small number of customers facing real-time prices provided a positive externality to the majority of households not facing real-time pricing (Borenstein and Holland 2005), the Texas event demonstrated that there were information and transaction-cost problems associated with real-time pricing options. Scaling up a pricing mechanism without addressing these problems seems unlikely to make it an effective tool in achieving large-scale demand reductions. Further, utilities often note that there is a duration problem with asking customers to conserve energy for long periods of time, even with price incentives. As a result, real-time pricing may not have been effective for an event of such long duration. Lastly, the event illustrates the problem of exposing residential customers to bill volatility that price spikes can cause. Economists have suggested coupling dynamic pricing with hedging (Borenstein 2007; Borenstein 2021) or less extreme forms of dynamic pricing than real-time pricing, such as residential CPP programs that focus calls on days in which the system capacity is strained (Borenstein 2017). In the aftermath of the crisis, the Texas Legislature adopted House Bill (HB) 16, which prohibits wholesale-indexed products including a direct pass-through of real-time prices for residential customers. It is unclear whether, going forward, the PUCT may still allow for residential products with indirect pass-through or partial hedges (Littlechild and Kiesling 2021).

4. *Recommendation 3*: Make infrastructure systems work better together – market and planning reforms that recognize interdependence

The 2021 Texas electricity crisis clearly illustrates critical infrastructure interdependencies. Many different types of energy infrastructure—from pipelines to refineries—, as well as communications and water systems, depend on electricity to function; as such, they may be unable to operate in a power outage, even if otherwise undamaged. Failures that cascade across infrastructures may also involve feedback loops that magnify the extent of the failures. Figure 1 shows the nature of infrastructure interdependencies contributing to blackouts during Winter Storm Uri.

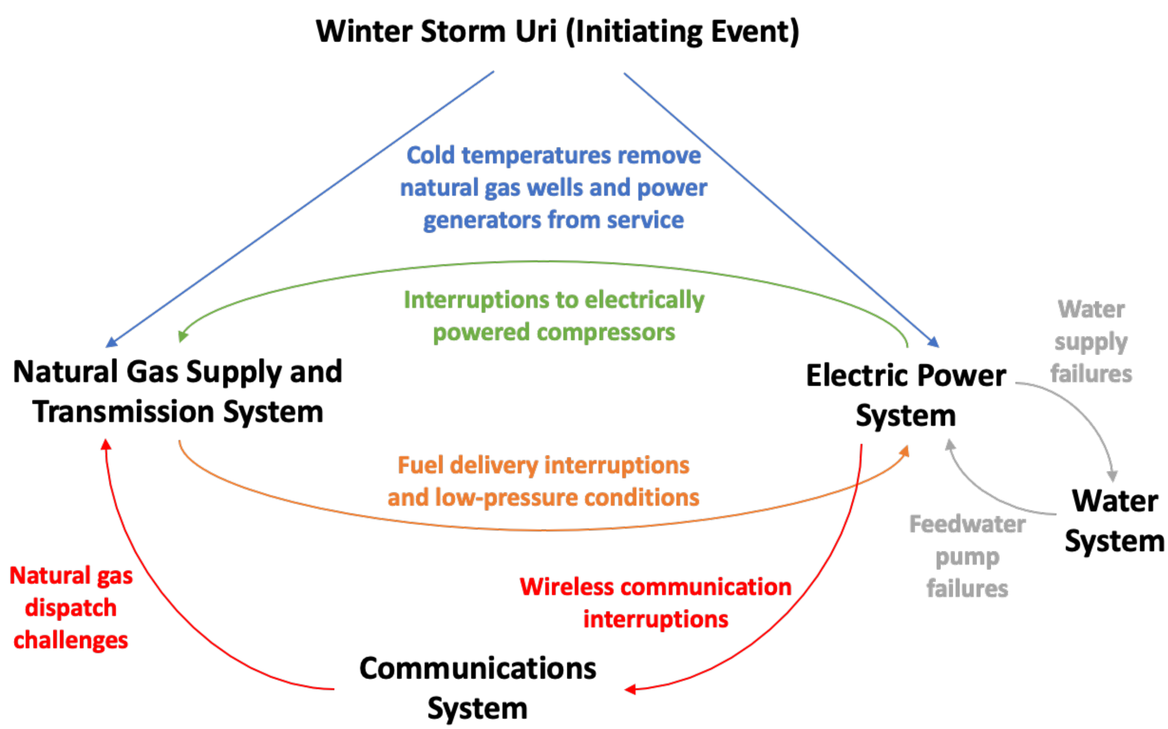

FIGURE 1: Critical infrastructure interdependencies.

Source: Own elaboration.

Water and communications systems were deeply impacted by power shortages during the Texas crisis. Pumping and treating water for public water supply systems requires significant amounts of electricity. Thus, electric power outages prevented treatment centers from properly treating water, causing disruptions at more than 1,000 public water systems in Texas (Oxner 2021). In turn, water system failures magnified the extent of the problems in the electric power sector: a weather-related disruption in a feedwater pump to a nuclear reactor in Texas caused the plant to shut down for two and half days during Winter Storm Uri. Turning to the communications system, interdependencies between energy systems and communications infrastructure indirectly affected reliable operations during Winter Storm Uri. Blackouts instituted by ERCOT and the storm itself led to communications outages that impeded the ability of gas pipeline operators in Eastern Texas to redirect gas supplies.[5]

A full exploration of the interdependencies between energy, water and communications systems is beyond the scope of this paper. We focus instead on the interdependencies between the electric power and natural gas industries. Consider the natural gas supply and transmission system first. Texas produces about 25% of the country's natural gas (U.S. Energy Information Administration 2022f) and consumes about 60% of its production (U.S. Energy Information Administration 2022d, 2022f). In winter, about 15% of natural gas is used in the residential and commercial sector to directly heat homes and buildings, and about 40% is used to supply power plants (Energy Information Administration 2022e, 2022g, 2022h, 2022i). Over the past decade, ERCOT has been substantially more dependent on natural gas for electricity generation than other regions in the United States (Figure 2). Further, as noted above, a key driver of winter electricity peaks is demand from homes that use electricity for heating. During tight system conditions, power generators have a subordinate claim for gas relative to local distribution companies (LDCs), even if they have firm contracts for pipeline capacity (MIT Energy Initiative 2014). This further exacerbates challenges to maintaining the reliability of the electricity system under grid emergency conditions, as observed in February 2021.

[5] Eastern Texas experienced fewer wellhead supply disruptions than Western Texas. Busby et al. (2021) note that "Permian gas production is highly electrified (and therefore affected by power outages) and liquids-rich (and therefore at risk of freeze-offs)." While differences in freeze-off rates during the 2021 event are not readily available, more freeze-offs in Western Texas would be consistent with the characteristics of Permian gas production.

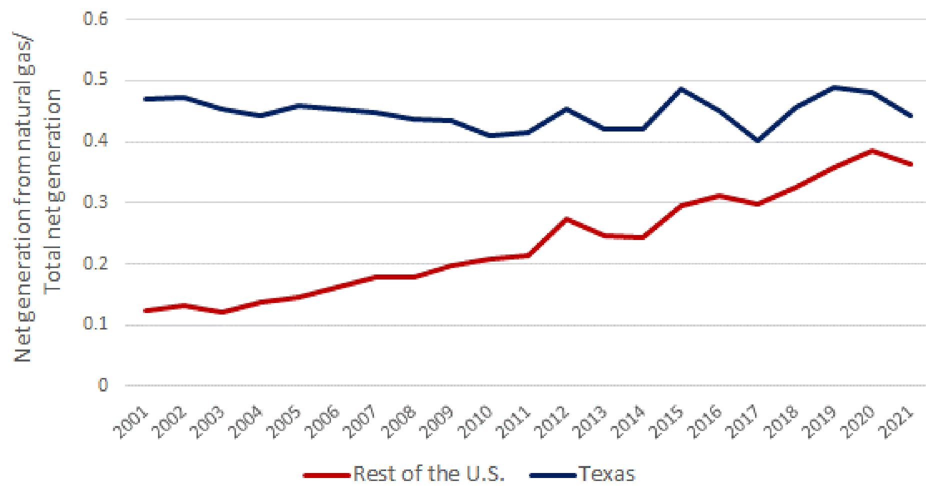

FIGURE 2: Share of net generation from natural gas in the electric power sector.

Source: U.S. Energy Information Administration (2022a).

Lack of winterization of natural gas production and midstream was a major cause of electricity shortages during the crisis. In fact, FERC and NERC had recommended that natural gas supplies in Texas should take steps to winterize after a major power outage in February 2011 (Federal Energy Regulatory Commission and North American Electric Reliability Corporation 2011), but only limited voluntary action was taken. Freeze-offs at wellheads and frozen delivery infrastructure, as well as low-pressure conditions in the natural gas pipeline system, created fuel delivery shortages to gas-fired power plants, regardless of the nature of their supply and shipping contracts. As a result, between 5 and 7 GW of gas-fired electric generation capacity that was scheduled to operate between February 15 and 17 could not be dispatched due to fuel limitations (ERCOT 2021b).

Compounding the weather-driven failures on the natural gas supply system that cascaded into failures on the power grid was the dependence of some portions of the natural gas supply system on electricity supply. Like other areas in the U.S. (as shown in Figure 3), portions of the natural gas transmission grid in Texas rely on electricity to power compressors, which maintain sufficient delivery pressure in the gas transmission system. The choice to use electricity for compression rather than harvesting natural gas from the pipeline system has been made for several reasons, including compliance with local air quality regulations and land use considerations (electric compressors require a smaller physical footprint). This choice does leave the natural gas transmission system vulnerable to extended power grid interruptions.

ERCOT permits certain electrical loads, including natural gas compressor stations, to register as critical equipment that should not be curtailed in emergency cases where ERCOT needs to ration electricity or institute rolling blackouts. While data is difficult to obtain, it appears that the vulnerability of the natural gas system to electrical blackouts in ERCOT was increased by the number of gas facilities in Texas that were not registered with ERCOT as critical loads at the beginning of the Winter Storm Uri event.[6] As part of SB 3, passed in the wake of the crisis, an expanded process has been implemented for designating portions of the state's natural gas supply system as "critical customers" to whom electric service should be maintained even if ERCOT is required to shed firm load during a contingency.

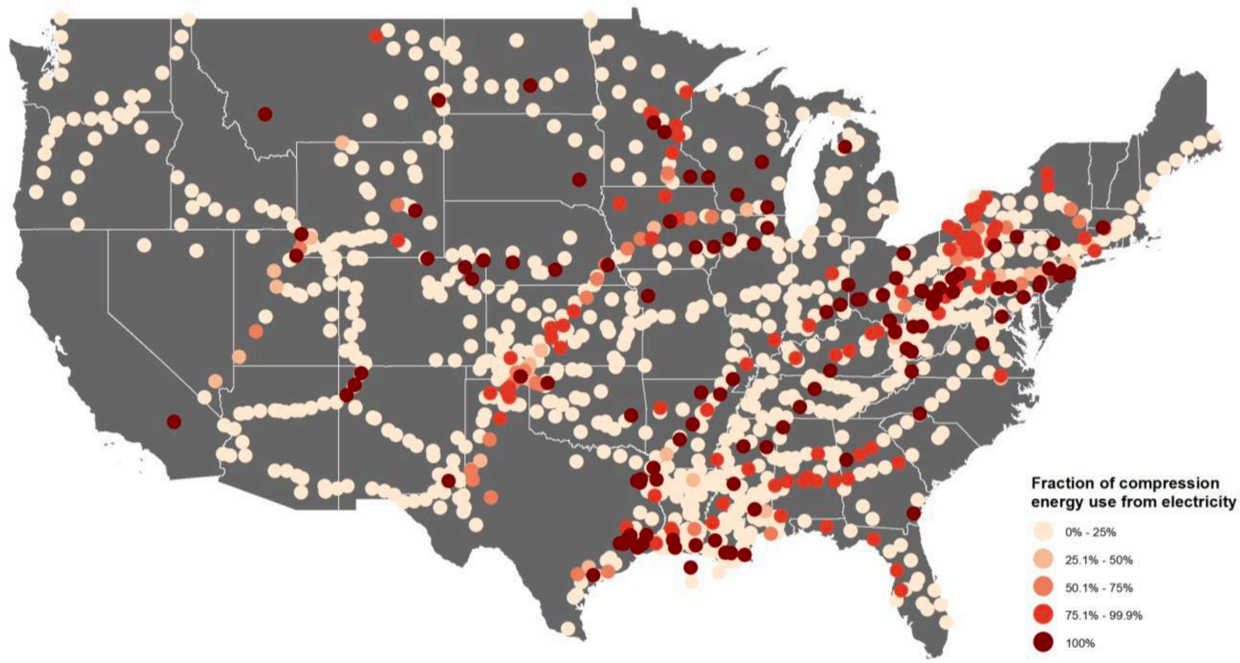

FIGURE 3: Natural gas compressor stations on transmission pipelines in the United States.

Source: Freeman (2019).

SB 3 also addresses weatherization of the natural gas system. At the end of 2021, the Texas Railroad Commission (RRC) enacted rules that designate large portions of the natural gas supply system as critical for the electric power grid. These rules also require the PUCT and the RRC to jointly identify physical points of interdependence where reliable gas supply is critical to reliable power grid operations. Gas facilities that meet the critical designation and are identified as being located in critical areas would be required to weatherize. As of the time of writing, these provisions have not yet been implemented, and the weatherization requirements for gas facilities established by the RRC are not as prescriptive as the requirements for power plants issued by the PUCT (Railroad Commission of Texas 2022). Further, since the physical points of interdependence are considered proprietary infrastructure information, the extent of gas system preparedness for future extreme winter weather is not clear.

The 2021 Texas crisis illustrates that disruptions may arise due to the simultaneous failure of multiple infrastructures owing to a common cause such as Winter Storm Uri. We discuss two options to enhance the reliability of the bulk power system by accounting for its interdependencies

[6] For example Oncor, Texas' largest utility, had classified only 35 gas facilities as critical before the event, and added 168 facilities to the list after the crisis (Michot Foss, Wood and Perlman 2021).

with the natural gas system. First, many recent supply shortage events in winter have been driven or exacerbated by competition for gas between heating and electricity generation. As previously discussed, natural gas shipping priority is currently given to LDCs meeting the heating needs of residential and commercial customers, creating additional challenges to maintaining grid reliability under emergency conditions. This approach also fails to recognize that natural gas furnaces will not work without electricity in most cases, and electric heat has been growing.[7] An allocation of scarce natural gas between competing uses that provides economically efficient and acceptable social solutions would enhance grid reliability against the threat of extreme weather. Economists have long advocated reforms in the natural gas market to help ensure reliable electricity supply (Bushnell 2021; Cramton 2022), but action has been slow.[8]

A second improvement would be enhancing resource adequacy and planning processes in the electric power sector to better capture critical infrastructure interdependencies and associated vulnerabilities. A broad consensus on the benefits of integrated multi-sector energy infrastructure planning exists, but actual implementation by planning entities is rare.[9] Yet, efforts are under way in some regions. For example, in April 2022 ENTSO-E and ENTSOG (the European Network of Transmission System Operators for Gas) published the gas and electricity joint Scenario Report. Scenarios in the Report outline the evolution of the European energy system towards 2050 and provide a basis for the Ten-Year Network Development Plan (TYNDP), a pan-European long-term planning study of the electric power sector (ENTSO-E 2022; ENTSO-E and ENTSO-G 2022). Notably, the scenarios utilize sector-coupling modeling tools and methods that account for the interactions and dynamics at the interfaces between the electric power and natural gas systems. The situation in the U.S., on the other hand, is marked by substantial policy fragmentation, in which "decisions by myriad market actors and institutions do not typically reflect coordinated information about the performance of systems either across industry segments (e.g., across the electric and gas industries) or within industry supply chains (e.g., from production sources across interstate transmission systems)" (National Academies of Sciences, Engineering, and Medicine 2021). The Texas Reliability Entity (TRE), one of the six regional entities under NERC authority, supports development and promulgation of reliability standards for the ERCOT power grid, including compliance. Unlike other areas of the continental U.S. power grid, however, the ultimate enforcement authority around reliability standards in Texas is the PUCT, since FERC lacks jurisdiction over ERCOT.[10] The grid operator is also subject to more direct oversight by the PUCT

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[7] Since 2010, 62% of homes built in Texas since 2010 use electric heating (Davis 2021).

[8] The joint FERC-NERC report on the February 2021 cold weather outages recognizes the issue, and recommends market/public funding for generators to have firm transportation and invest in storage contracts. Such funding would "finance the infrastructure (e.g., pipeline or storage expansion) necessary to provide additional firm transportation capacity, because many existing pipelines were financed and constructed to serve Local Distribution Companies and may not have sufficient additional firm capacity ….. to support an increase in demand from generators" (Federal Energy Regulatory Commission, North American Electric Reliability Corporation, and Regional Entities 2021 – Recommendation 24).

[9] One of the primary difficulties associated with multi-sector planning is the development of realistic modeling frameworks to represent inter- and intra-sectoral dynamics at the required spatio-temporal scales. Modeling issues are also associated with the characterization and quantification of uncertainties in multi-sector models (Kakodkar et al. 2022).

[10] However, FERC may issue recommendations for the electric power sector in Texas, as it did in February 2011 with voluntary guidance on winterization of power generation units.

(which regulates the state's electric, telecommunication, and water utilities) and the Texas Legislature (which can change the rules of market and regulatory designs). In the natural gas sector, some aspects of natural gas production are subject to regulation, and the RRC has regulatory jurisdiction over oil and gas wells located in Texas. An equivalent institution to NERC in the natural gas industry does not exist, and FERC does not have authority to adopt reliability standards, as it does with respect to the wholesale electric industry.[11]

5. Conclusions

The February 2021 cold weather outages in Texas remain a subject of important study and investigation, and lessons learned from the event have broader relevance for bulk power systems around the world. In our view, the major causes of the crisis were not due to wholesale electricity market design, but to problems in planning and awareness of system interdependencies. We discuss three systems-level strategies to enhance bulk power system reliability against the threats of extreme weather. Two of these strategies, in particular, have received limited attention in previous analyses.

First, generation resource adequacy and planning processes in the electric power sector should be enhanced to include multiple adverse conditions occurring simultaneously, common mode failures, growing system variability and potentially severe future weather events as part of the calculus. Actions to enhance understanding of the potential impacts of climate change on system load and resource availability are being undertaken in other regions of the U.S. and Europe. The Texas crisis also illustrates that performance incentives and non-performance penalties do not fully solve the market failure due to the misalignment between social welfare maximization and private objectives. Further, markets are not well suited for managing risks associated with catastrophic events, and private incentives often do not provide efficient and socially acceptable solutions under such circumstances. As a result, regulation and standards will likely play an important role to ensure provision of reliability against the threat of extreme weather.

Our second recommendation centers around demand-side solutions, which are vastly underutilized to address reliability challenges. Tools such as energy efficiency in homes, customer-side curtailment beyond existing industrial and commercial programs, and dynamic pricing options that do not expose residential customers to bill volatility could reduce peak demand during emergency conditions. Opportunities for improvements in this area are likely larger for Texas than in other regions of the U.S. Further, in our view time-varying pricing should not be abandoned just because of what happened in Texas, although it may not be effective for long-duration power interruptions.

Third, resource adequacy and planning processes in the electric power sector should evolve to better capture critical infrastructure interdependencies and associated vulnerabilities. Strengthening alignment of planning and operating practices across the electric and natural gas industries is especially important, but poses practical implementation challenges in settings where decisions are

[11] A recent report by the National Academies recommended that FERC be given authority to designate a central entity to oversee and establish standards for the operational reliability of the natural gas delivery system (National Academies of Sciences, Engineering, and Medicine 2021, Recommendation 3.2).

made by myriad market actors and institutions. Further, reforms in the natural gas market that improve fuel allocation between local distribution companies and power plants during periods of scarcity would help support electric system reliability.

The most significant energy-related bills passed by the Texas Legislature to date will result in a $18-billion out-of-market directive to build up to 10 gigawatts of new natural gas-fired power plants sitting in reserve; substantial changes to the governance of ERCOT and certain aspects of the ERCOT market (e.g., emergency pricing); a mandate for electricity suppliers in the state to purchase dispatchable power services as insurance; and the ban of wholesale-indexed products that include a direct pass-through of real-time prices for residential customers. To varying extents, these steps are reactions to a particular event, and may address pieces of what was a highly complex failure across multiple infrastructure and regulatory systems. However, enhancing grid reliability against the threat of extreme weather will require more systems-level reforms.

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