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Cascading risks: Understanding the 2021 winter blackout in Texas

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ABSTRACT

The Texas freeze of February 2021 left more than 4.5 million customers (more than 10 million people) without electricity at its peak, some for several days. The freeze had cascading effects on other services reliant upon electricity including drinking water treatment and medical services. Economic losses from lost output and damage are estimated to be \$130 billion in Texas alone. In the wake of the freeze, there has been major fallout among regulators and utilities as actors sought to apportion blame and utilities and generators began to settle up accounts. This piece offers a retrospective on what caused the blackouts and the knock-on effects on other services, the subsequent financial and political effects of the freeze, and the implications for Texas and the country going forward. Texas failed to sufficiently winterize its electricity and gas systems after 2011. Feedback between failures in the two systems made the situation worse. Overall, the state faced outages of 30 GW of electricity as demand reached unprecedented highs. The gap between production and demand forced the non-profit grid manager, the Electric Reliability Council of Texas (ERCOT), to cut off supply to millions of customers or face a systems collapse that by some accounts was minutes away. The 2021 freeze suggests a need to rethink the state's regulatory approach to energy to avoid future such outcomes. Weatherization, demand response, and expanded interstate interconnections are potential solutions Texas should consider to avoid generation losses, reduce demand, and tap neighboring states' capacity.

1. Introduction

When Winter Storm Uri struck Texas in February 2021, more than 4.5 million households (roughly 10 million Texans) were left without electricity at its peak, some for several days [1]. What locals called “the Texas freeze” had cascading effects on other services reliant upon electricity including drinking water treatment and medical services [2]. With temperatures plunging inside people's homes, some took shelter with friends and family despite the COVID-19 pandemic or sought temporary refuge at warming stations. Others took extraordinary measures to try to warm themselves – using their ovens to heat their homes or burned fences and furniture for warmth – which led to carbon monoxide poisoning and home fires. As of March 2021, at least 111 people are known to have died during the freeze [3]. AccuWeather estimated economic losses from lost output and damage to be \$130 billion in Texas

alone and \$155 billion for the country as a whole [4].

Prior to the freeze of February 2021, Texas' largely self-contained electric grid was seen by some as a model of efficiency, with a combination of smart market design, light regulation, and the ability to combine firm baseload power and large amounts of wind energy from far-flung parts of the state [5,6]. The 2021 freeze shook confidence in that model.

While previous cold weather events had affected the state, including severe freezes in 1989, 2003, and 2011, none affected as many people or were as long-lasting. So, what went wrong?

Months after the event, we can offer a more comprehensive retrospective on what caused the blackouts and the knock-on effects on other services, the subsequent financial and political effects of the freeze, and the implications for Texas and the country going forward. These are especially important questions in the midst of a worsening climate crisis

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and the need to pursue a clean energy transition.

What follows is (1) a summary of core observations, (2) a review of why the outages were so severe, (3) how to apportion responsibility for the failure, and (4) what steps could be taken to ensure that weather-related energy crises do not lead to catastrophic outcomes in Texas again. We conclude with lessons that can be applied more broadly.

2. Summary observations

Texas failed to sufficiently winterize its electricity and gas systems after 2011, and the feedback between failures in the two systems made the situation worse.

At its depth, gas production declined by nearly 50% [7], which lowered pressure in the pipelines, making it harder for power plants fueled by natural gas to operate. Overall, the state faced outages of 30 GW of electricity as demand reached unprecedented highs [8]. Other sources of electricity – nuclear, coal, and wind – also suffered from supply disruptions but these were smaller than the loss of generating capacity from gas power plants.

The gap between production and demand forced the non-profit grid manager, the Electric Reliability Council of Texas (ERCOT), to cut off supply to millions of customers or face a systems collapse that by some accounts was minutes away [9]. The fact that most of Texas is part of the ERCOT grid and by design is largely disconnected from neighboring grids meant that Texas could only import a very limited amount of excess electricity from its neighbors (see Fig. 1).

While the physical effects on families were shocking and severe, the financial repercussions will last decades as ratepayers may be saddled with some \$50 billion in power bills as prices spiked to encourage more production to come on-line. There were also unexpected gas bills, likely in the billions, for gas utilities but that total amount is difficult to estimate at this time. Multiple high-profile lawsuits are underway challenging these bills and there will be efforts to shield consumers from having to pay exorbitant prices and utilities from being saddled with crippling debts.

With climate change continuing, it is reasonable to expect Texas could face more frequent and intense extreme weather events, further straining the system unless planners prepare appropriately. This underlying context is relevant for other regions. As Webber argued, “The experience in Texas should be a warning to other states: If an energy-abundant, rich state that likes to invest in infrastructure can suffer a significant energy crisis, then it can happen anywhere” [10].

3. Why were the outages so severe?

3.1. What happened

Severe, but not unprecedented, cold weather led to a spike in energy demand.¹ Temperatures in Austin, for example, dropped from 32°F (0 °C) on February 11th, to just below freezing on the 12th and 13th, before plummeting to 14°F (−10 °C) on Sunday the 14th, and declining to 6°F (−14 °C) on the 15th. Shortly after midnight on the 15th, 8000 MW of gas power plants shut down because of fuel shortages or freezing equipment and 2000 MW of wind went offline due to low winds, frozen equipment such as substations, or precipitation that caused ice formation on turbine blades [13]. With projected demand significantly exceeding supply, ERCOT ordered firm load shed (blackouts) on Monday the 15th at 1:25am to prevent the collapse of the grid (see Fig. 2 below) [8,14]. As Bartholomew noted, the state’s extreme winter planning scenario estimated at most 14 GW of outages, but by Monday morning, more than 30 GW of generating capacity was unavailable [15].

¹ There have been other cold spells of similar magnitude. While 1989 and 2011 are frequently mentioned, December 1983 and February 1985 were also comparable cold periods.[11], [12]

Texas gets most of its electricity from natural gas (46% in 2020), with smaller shares provided by wind and coal (23 and 18% respectively), followed by nuclear (11%), solar (2%), and marginal contributions from hydroelectric and biomass [16].

While wind power provides more than 20% of the state’s electricity needs over the course of the year, it is a resource whose availability changes by location, time of day and time of year. As such, grid operators use seasonal expectations for wind’s contribution to grid generating capacity for their reliability planning. The forecast for this period suggested wind production would only provide about 7% of the state’s power demand [17], with an expected hourly output of 6.1 GW for wind compared to the installed capacity of 28 GW. Knowing this, ERCOT did not plan for much generation from wind during this period.

Natural gas, coal, and nuclear were expected to serve as the firm baseload power that could be relied upon. However, that proved not to be the case, particularly for gas-powered electricity, though all fuel sources faced some challenges from the winter weather. Electricity generation and gas supply problems contributed to severe shortfalls of both electricity and gas. For much of the crisis, load shed was around 15–20 GW, about a quarter of the projected peak electricity demand during the winter peak. Around 30 GW of gas, coal, and nuclear were offline during the crisis [18].

Based on ERCOT’s 2020 seasonal winter resource adequacy assessment [19], Shaffer calculated the performance of different fuel sources during the 4-day freeze period (3/15–3/19) compared to their expected winter capacity as well as an extreme scenario [75]. All major fuel sources underperformed against expectations save for solar. Natural gas was responsible for nearly $\frac{2}{3}$ of the total deficit. Gas underperformed by 37% compared to its expected output – more than 18 GW below expectations – and was 21% below the extreme scenario. Coal was 43% below expectations and 28% below the extreme scenario. Wind was 46% below expected but better than the extreme weather scenario. One of Texas’ four nuclear reactors was offline for 2.5 days during the freeze due to a feedwater pump issue [20–22], which meant that nuclear underperformed by about 20% (see Table 1 below).

3.2. Cascading risks and correlated failures

Texas has a prominent natural gas sector that produces nearly 25% of the country’s total and is a larger producer than every country in the world except for Russia and the United States. In 2019, Texas consumed just over half the gas it produced, the remainder exported out of state [23]. Texas’ inability to supply its own needs during the 2021 winter freeze was thus all the more striking.

In summer, nearly all the natural gas used in Texas for the commercial and residential sectors is consumed indirectly from electricity generation, but in winter, natural gas is also used to directly heat homes and buildings in addition to supplying power plants that indirectly provide heat with electricity. About 60 percent of Texans’ homes are heated with electricity, the remainder mostly with gas (and propane for a small fraction of homes) [24].

The primary culprit for the electricity system failure was problems in electricity production from natural gas. About 40% of natural gas production was not available during the crisis. Texas’ gas, electricity, and water systems are inter-linked so failures in one of them can lead to cascading effects on the others [25]. The natural gas system relies on electricity, and the electrical system relies on gas. Thus, constrained gas limits the ability to generate electricity and constrained electricity limits the ability to supply gas which in turn further limits the ability to generate power in a vicious circle. Power outages in turn can lead to failures in the water supply [10].

Ravikumar summarized four failures in supply chains that ultimately led to a sharp drop in electricity from gas at the height of the crisis, (1) freezing at natural gas wells, (2) freezing of gathering lines, (3) power outages at compressor stations, and (4) equipment malfunctions at power plants [26]. Power plants themselves faced their own challenges

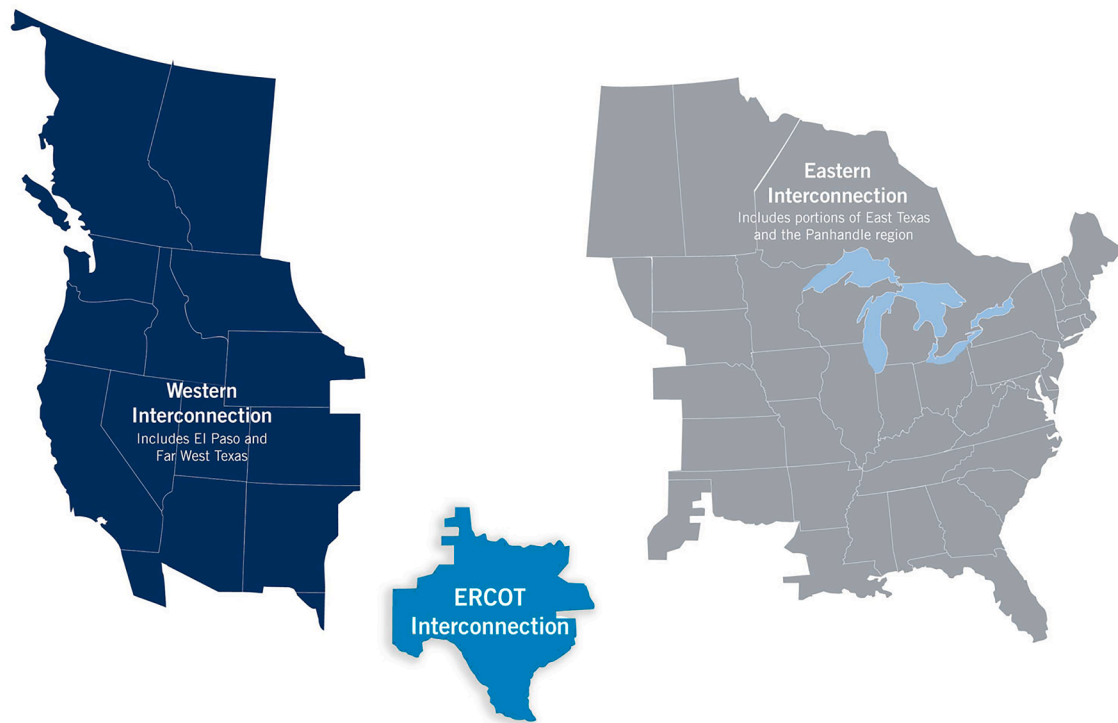


Fig. 1. North American Interconnections Map.

Extreme Weather, Extreme Outages Pushed Texas into Blackouts

ERCOT electric load, load forecasts, thermal plant outages, and renewables

80GW

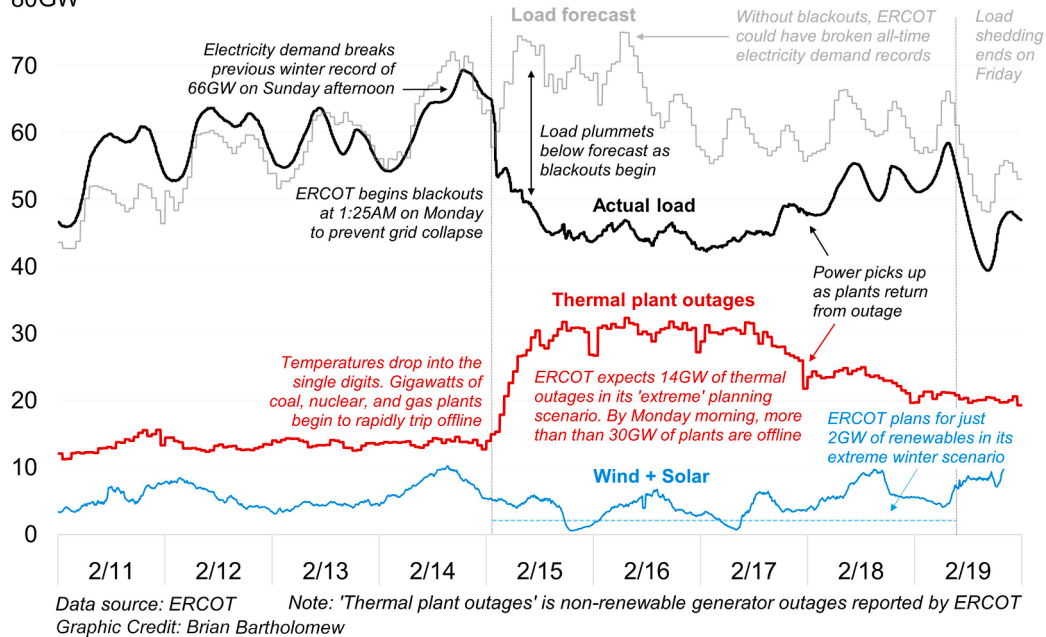


Fig. 2. Demand Growth and Power Outages During the Texas Freeze.

operating in cold weather, as many power stations in the southern United States are not contained in buildings; doing so reduces the risk of overheating during warm periods but leaves them exposed during the cold [27].

One reason gas producers lost power is that many of them

intentionally sign up for interruptible power contracts as a way to reduce their electricity bills. Furthermore, a significant number of them did not fill out a short form requesting that they be identified as critical infrastructure, compounding the problem. Electricity providers unwittingly shut power off to some gas production and processing facilities,

Table 1
Comparison of Fuel Sources: Expected Capacity and Actual Generation, February 15–19th.

Fuel Source	Expected capacity (GW)	Extreme Scenario Capacity (GW)	Actual Average Generation (GW)	Deficit (GW)	% Deficit [From Expected Capacity]	Deficit Extreme Scenario (GW)	% Deficit [From Extreme Scenario Capacity]
Gas	48.4	38.4	30.3	−18.1	−37%	8.1	−21%
Coal	13.6	10.8	7.8	−5.8	−43%	3	−28%
Wind	7.1	1.8	3.8	−3.3	−46%	−2	111%
Nuclear	5.2	4.1	4.1	−1.1	−21%	0	0%
Solar	0.3	0.3	0.77	0.47	157%	−0.47	157%

Source: ERCOT data compiled by Blake Shaffer.

which reduced gas pressure further, thereby forcing more generating capacity offline when fuel was unavailable for gas-fired electricity plants. According to ERCOT, more than 9 GW of outages, about 20% of the total and enough for 1.8 million homes, resulted from insufficient gas supplies reaching power plants [28]. A similar sequence of events had occurred in 2011, and post-event regulatory reviews had warned of this problem's ongoing risk, but little had been done by the gas industry to rectify it. A number of producers entered the market since 2011 and were unaware of the form they needed to fill out to request this designation. For example, in the midst of the freeze, Oncor, a utility, turned on the power to 150 gas facilities in the Permian Basin after receiving frantic calls that they had been turned off [29]. In addition, the shale boom in the Permian mostly occurred since 2011, which exacerbated risks: Permian gas production is highly electrified (and therefore affected by power outages) and liquids-rich (and therefore at risk of freeze-offs).

Another reason less capacity was available is that a number of thermal plants were down for scheduled maintenance to take advantage of Texas' normally mild winters when demand is low. This schedule is typically interpreted as good planning because it was intended to ensure sufficient reserve in summer time. ERCOT in its seasonal winter maintenance schedule had forecast 4 GW of scheduled maintenance. Analysts from Wood Mackenzie wrote that the actual amount of plants down for outages in the week leading up to the freeze was more like 14 GW, consistent with what happens annually in so-called "shoulder season" when demand is light. ERCOT in the week prior to the freeze tried to induce some plants to come back by issuing a Operating Condition Notice, but they noted plants were unlikely to be able to secure gas on short notice and could and did disregard the request, with 14 GW still offline going in to Monday morning [30,31].

3.3. It could have been worse

As the crisis unfolded, demand rose rapidly to 66 GW on the afternoon of February 14th. ERCOT's maximum demand in its extreme winter scenario was 67.2 GW, but in the midst of the crisis, peak generation reached 68.8 GW on February 14th and demand was forecasted to rise to 76.8 GW on the 15th [14]. As demand rose and supply fell, ERCOT declared an Energy Emergency Alert (EEA) Level 3 for the first time since February 2011 and ordered load-shedding the early morning of February 15th, which had to be ramped up as more plants and gas facilities failed.

Because these generation shortfalls were so large, what was initially expected to be rolling blackouts became, for many customers, including several authors of this paper, a multi-day power outage (also known as a "controlled outage" rather than a "rolling outage"). With available power reserved for critical infrastructure such as hospitals and fire stations, there wasn't enough spare capacity to rotate outages.

Demand for power has to be tightly matched to supply. Grids based on alternating current need a frequency within a very narrow margin of 60 Hz in the U.S. to maintain stability. Below a frequency of 59 grids face cascading blackouts that can cause the entire grid to shut down. ERCOT thus avoided a complete shutdown which would have led to power outages for 26 million Texans covered by the Texas grid. On the morning

of February 15, the Texas grid's frequency declined to below 59.4 Hz for four minutes and 23 seconds. Had it remained there for a full 9 min, ERCOT said the grid would have collapsed, leaving much of the state in darkness (see Fig. 3) [9,32,33]. At its peak on February 17th, nearly 49% of the grid capacity (52.2 GW out of 107.5 GW was offline) [34].

With this close call, the entire system was within minutes of collapse, which would have required a "black start" that could have taken days if not weeks (or even months) to implement. To restart would require a slow process of starting individual plants and then building the grid back up gradually.

3.4. The impacts on Texans

Some Texans bore the brunt of the outages. At its worst, 4.5 million metered customers experienced power outages,² including a large proportion of customers in some counties around Fort Worth, Austin, and Houston (see Fig. 4). In absolute terms, the largest numbers without power were in Dallas, Austin, and Houston, each of which had more than 300,000 metered customers without power, about 700,000 people in each city [17]. In advance of the freeze and throughout, communication from state leaders about what to expect, how to prepare, and available resources was scant at best, leaving people to suffer indefinitely while waiting for the power and/or water to come back on [35].

While many Texans rely on electricity for heat, even those with gas-fired furnaces were unable to heat their homes in many cases given that modern furnaces have electric controls. Simpler gas furnaces or fireplaces with manual controls continued to work. While some were able to take refuge with friends, family, hotels or warming stations, unplowed and unsalted road conditions made it difficult for people to switch locations, particularly the elderly. With power and gas interruptions, many people experienced unsafe temperatures inside their homes. Some took dangerous steps to heat their homes, including using gas ovens, trying to stay warm in a car (raising risks of carbon monoxide poisoning), or indoor fires (raising risk of burns or deaths). In a state with a significant homeless population, the impacts of the storm on those populations were no doubt severe and difficult to quantify. Over a hundred deaths have been documented during this period, though this is likely an undercount.

The Texas Energy Poverty Research Institute (TEPRI) surveyed 953 Texans about what they experienced: 75% of the respondents lost power at some point, with 33% losing power for two days or more. Only 25% lost natural gas during this period (Texas law prioritizes residential gas customers over industrial customers or power plants), but as noted above, many houses heated with gas couldn't turn the gas on because of the loss of power. Of respondents, 27% used the oven to stay warm, 65% had to boil water, 40% went two days or more without clean water, 30% lost running water for two days or more, and 2% remained without water when the survey was conducted nearly two weeks after the event. Many households experienced significant plumbing issues with burst

² An important point is that 4.5 million customers lost power, which is around 10 million people/Texans. Usual rule-of-thumb is 2.5 people per customer.

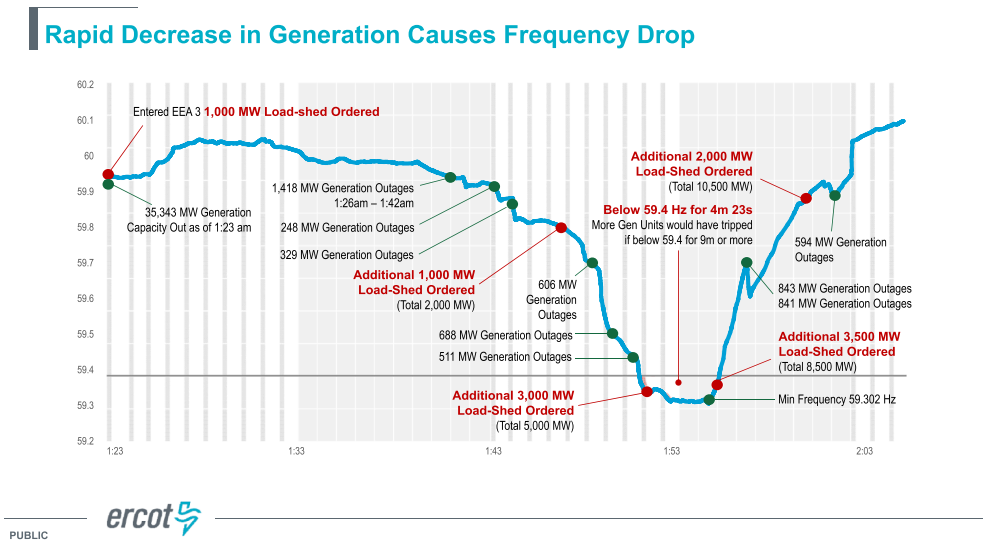
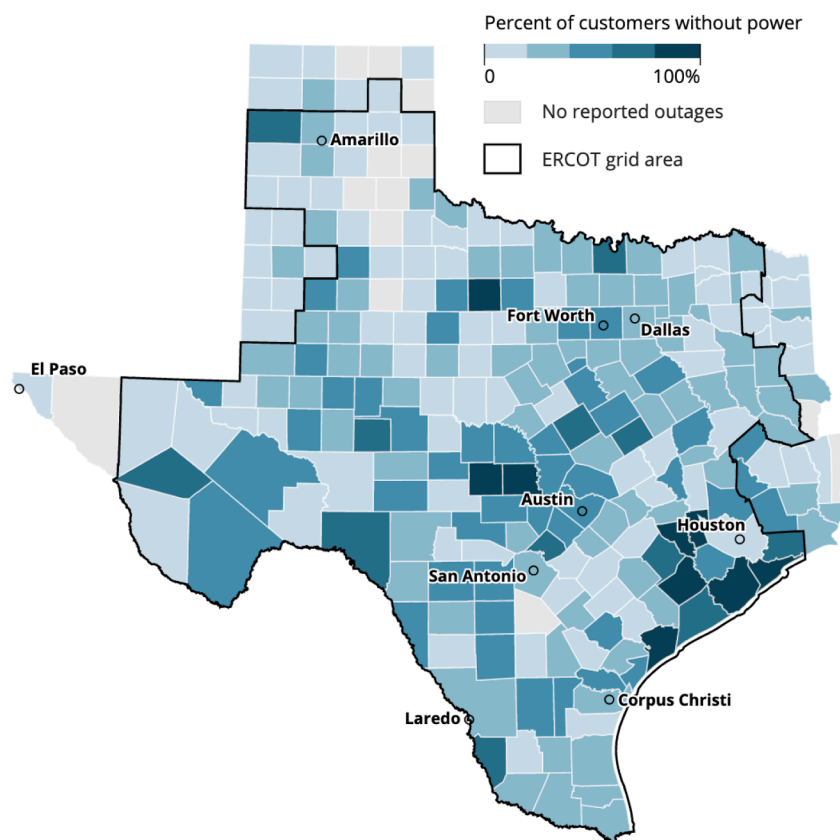


Fig. 3. ERCOT's Frequency Drop on February 15th.



Source: The Texas Tribune and ProPublica

Fig. 4. Texans Experiencing Power Outages on February 16, 2021.

pipes and water heaters, sometimes sustaining home damages at a time when plumbers and plumbing parts were scarce. The survey shows that 15% fled to hotels, friends, family, or warming shelters, but 40% of these shelters too lost power, water, or both. In addition, 28% reported using their car for warmth, 20% used snow for water, 20% burned wood, and 20% had access to a generator [36].

While all socio-economic groups were affected, the storm was especially hard on low-income families who live in older, poorly

insulated homes, with worse plumbing, and limited resources to relocate, repair home damage, or replace spoiled food [37]. Low-income people, particularly communities of color, had already been disproportionately affected by the coronavirus, in terms of the disease burden and unemployment, so the freeze further compounded their physical well being and finances [38]. A 2020 survey of Houstonians, for example, found that half of Black and Latino respondents could not come up with \$400 for emergency expenses [39].

4. The regulatory and financial fallout

In the wake of the freeze, there has been major fallout among regulators and utilities as actors sought to apportion blame and utilities and generators began to settle up accounts. Among regulators, there has been a spate of resignations and firings at the Public Utilities Commission of Texas and ERCOT, for example, while several companies and utilities have declared bankruptcy.

4.1. How energy in Texas is regulated

Texas has a unique regulatory structure for energy, with oil and gas regulation covered by a different agency (the Railroad Commission) than electricity (Public Utility Commission of Texas), which oversees ERCOT, whose responsibilities are specific to managing the grid that covers most Texans' electricity needs.³ ERCOT is also unique, as it operates with an "energy-only" market, which means power plants are only paid if they generate electricity. Other regions have capacity markets, where some operators are paid to have backup capacity whether or not they run [24]. It is not clear that a capacity market would have helped in this crisis, since 1) the additional capacity would likely have been only a few GW (far short of the 30+ GW that was offline) and 2) extra generating capacity might not have been able to turn on given failures of gas supplies.

While ERCOT manages the grid, the three-member Public Utility Commission (PUC) of Texas, appointed by the governor, controls the maximum prices generators can charge. ERCOT acts as the clearing-house for payments from electricity buyers to electricity generators. In addition to those that supply and buy physical energy obligations, the ERCOT market included purely financial players, who help hedge or provide liquidity. The Texas Railroad Commission is tasked with regulating gas supplies. The Texas legislature has oversight responsibilities and can change the rules of market and regulatory design, as it did in 1995 and 1999 to deregulate the sector. In the wake of the freeze, the legislature has held hearings to hold actors accountable.

Because Texas has limited transmission grid interconnections with other states, electricity generation in Texas is largely unregulated by the Federal Energy Regulatory Commission (FERC). FERC has some oversight jurisdiction and issued voluntary guidance on weatherization after a similar freeze in 2011 [40,41]. ERCOT is part of the wider North American Electric Reliability Corporation (NERC), which like ERCOT is a non-profit organization, that establishes voluntary guidelines for reliability for the wider landscape of utility grids.

Despite the failures of many parts of the energy system, the power sector and renewables received most of the scrutiny and blame early in the aftermath of the storm, particularly by politicians. Since the freeze, as of mid-March 2021, ERCOT's CEO was fired and eight of fifteen ERCOT board members resigned. All three of the PUC commissioners have resigned. There has not been a similar response of resignations from the Texas Railroad Commission. One Railroad Commissioner, Wayne Christian, authored an op-ed in the *Wall Street Journal* blaming Texas' energy woes on wind power and climate policies and another Railroad Commissioner, Christi Craddick, said natural gas was part of the solution rather than a problem [76,77]. Four companies and utilities declared bankruptcy shortly after the crisis subsided, including Brazos Electric Power Cooperative, Just Energy, Brilliant Energy, and Griddy

Energy, and more are expected [78,79]. During the freeze, Griddy Energy was in the news for passing on wholesale prices to customers, which led to thousands of Texans facing extreme power bills, some in excess of \$10,000. Meanwhile, many gas providers have announced increased profits, revenues, share buybacks and increased dividends based on the strength of bumper sales of natural gas at very high prices during the 5-day storm [80].

The Texas market design normally allows for price discovery between buyers and sellers, with prices rising with demand. However, the PUC has the capacity to set prices to induce suppliers to enter the market. In those cases, the PUC establishes the price levels, and ERCOT implements them. There are two scarcity pricing mechanisms to induce extra supply, (1) a \$9,000 per megawatt hour (MWh) price cap and (2) two scarcity price mechanisms that automatically kick in to increase prices as reserves dwindle [42].

On February 15th and February 16th, the PUC filed orders that ended up setting prices through the Texas winter storm at the system-wide offer cap of \$9,000/MWh. Those prices remained in effect until the morning of Friday February 19th. When there is load shedding, the system design caps prices at \$9000 to reflect the value of lost load (VOLL). With prices that high, any generators that had spare capacity would enter the market to take advantage of high prices. Marginal producers may keep plants mostly offline such that they primarily operate in peak periods in summer and winter when they can make a healthy profit from the maximum prices. Pre-storm spot prices were about \$30/MWh [43].

Up until the price cap was set, prices on February 15th had only risen to \$1200 which the PUC judged as inconsistent with what was needed given that nearly 50 GW of power were offline. However, many producers had trouble reacting to these price incentives given that their operations were not adequately weatherized and gas supplies were curtailed. In other words, those power plants were not available at any price. At \$9000/MWh, electricity retailers were concerned they would be forced to pay more for electricity that was available and that the high prices were sustained for far too long [44]. In previous periods of scarcity, high prices remained in place for a few hours, with 16.75 h the previous maximum in 2011 [45].

ERCOT stopped shedding load from the grid by 11:55 pm on February 17th, but kept in place the pricing order until the 19th. That led Potomac Economics, the PUC's Independent Market Monitor, to issue a letter that said the pricing order had remained in effect for 32 h longer than it should have, leading initially to an estimated \$16 billion in excessive charges to electricity retailers during that period, out of some \$47 billion that was charged during the load shed event [46].

Subsequent legislative oversight hearings deliberated on whether those prices can or should be retroactively revoked and what repricing would entail. Some analysts observed that at the time ERCOT rescinded the load shed order, adequate electricity was not assured, potentially a reason to keep the pricing order in place at least for some period after the load shed order was terminated.

Potomac Economics noted that correcting the error will not reduce costs by the full \$16 billion for consumers since a significant share of the charges are from utilities that owned their own generation facilities or had hedged risk through forward contracts. So-called ancillary services associated with electricity did not have price caps and prices for these rose to almost \$22,000/MWh. Repricing would therefore only effectively cut charges by \$3.2 billion, rising to \$5.1 billion if ancillary services were also repriced. This move would shift the losses between parties from utilities to gas generators, but given that the gas supply market has not yet been proposed for repricing, the losing parties would mostly be gas generators. Political infighting had stalled debates about whether repricing should take place, and the issue will likely be litigated [47–49].

³ The Texas Commission on Environmental Quality (TCEQ) oversees emissions and the Texas Water Development Board has water resources in its purview, which affects power generation (because of the significant need for water cooling) and oil and gas production (because of the water requirements and wastewater disposal needs of hydraulic fracturing, plus the additional risks of freezefoffs in the extractive industries). This division of energy responsibilities across multiple agencies creates opportunities for mistakes, miscommunications, and oversights.

4.2. What should come next?

ERCOT's market design and planning have focused on summer peaks, which were historically the most challenging, and delivering sufficient electricity but not having a lot of extra reserve capacity during periods of high demand in winter and summer. For example, ERCOT's scenario for extreme winter demand and high outages only left a cushion of less than 1.4 GW reserve capacity in their worst case scenario [19].

While that had some advantages in terms of lower average costs, the 2021 freeze suggests a need to rethink the state's resilience to avoid future such outcomes. Supply and demand-side weatherization, demand response, and expanded interstate interconnections are potential solutions Texas should consider to avoid generation losses, reduce demand, and tap neighboring states' capacity.

4.3. The need for weatherization

Texas' electricity and wider energy system will likely face other weather-related emergencies, and severe winter weather is but one of them. No state can weatherize all its assets against all possible outcomes, so the question is what is the appropriate level of insurance that states like Texas should invest in to protect against rare events.

On the supply side, Texas has undertaken some efforts to protect its grid against more common summer weather demand spikes, but it has done little to protect itself against rarer winter freezes. However, these happen often enough that more winterization is warranted. Texas was advised to winterize by FERC after the 2011 freeze led to similar, albeit less catastrophic power outages of 4 GW. FERC suggested most winterization measures "would not be unduly expensive." For gas-fired units, the capital costs of equipment like insulation and heat tracing could range from \$50,000 to \$500,000. For gas producers, they estimated well winterization costs to range from \$2800 to \$30,000. For producers with hundreds of wells, these costs could add up [50]. Statewide, winterizing 50,000 to 200,000 wells could cost a few billion dollars. Notably, that expense is significantly lower than the cost of the crisis itself. Furthermore, winterization does not need to be implemented at every well. About six percent of wells produce 60% of Texas' gas output so the number of wells, pipelines, and equipment that require winterization to protect system wide robustness is relatively small [51].

The problem is that FERC's recommendations on weatherization of the power plants were advisory, and the state did not make weatherization mandatory. Nearly 1,800 units failed at 356 electricity generation facilities in 2021. While the identity of all the plants that failed in 2021 was not yet public, a partial list revealed that at least three dozen plants that failed in 2011 also failed in 2021 [52,53]. There are proposals in the Texas legislature to make weatherization mandatory, with others identifying funding mechanisms from tapping the state's rainy day fund (a surplus fund from revenue from oil and gas) to establish a revolving loan program or using federal COVID relief [54,55].

Simply winterizing gas production and gas-fired electricity plants is an important step in the direction of robustness, but is not adequate. The next challenge for ERCOT might be satisfying summer peak demand. In spring 2021, in the wake of the winter freeze, Texas experienced days of high temperatures and heavy demand that tested the ERCOT grid again, at a time when significant power generation was offline for maintenance and in some cases to repair damage from the storm. High summer temperatures and drought-induced water limitations for cooling could mean that the winter freeze was only the first of the state's cascading blackouts in 2021.

Demand side strategies in buildings and investments in energy efficiency throughout the state could reduce the need for electricity during periods of extreme cold or heat, thereby avoiding some of the strain in the first place. Texas consumes the most energy of any state in the country but ranks 29th in the country in terms of energy efficiency of its buildings [56]. Investments in heat pumps, LED lights, drill-and-fill insulation, among other measures could diminish energy demand in

Texas buildings, particularly important for low-income communities and communities of color [57,58].

4.4. Crisis information and the role of demand response

Texans did not receive adequate warning from the governor or other public officials to prepare for the storm and what steps they should take to protect themselves or reduce energy demand. This lack of emergency preparedness communications was notable and could have exacerbated risk to life and property.

As Rai said in testimony to Congress, "On the consumer side, there was an absolute lack of coordinated, consistent, and timely emergency communication to the people of Texas. Households and communities were clueless about what was happening, how to respond, and what to expect next." The Arctic front moved slowly southward over several days, so there was plenty of time for cities and residents to prepare if proper warning and communications had been issued. Information could have been shared that would have facilitated individuals and municipalities to prepare for the crisis. In addition, timely calls for voluntary conservation could have played a valuable role in dampening demand. As Rai noted, "A coordinated and clear extreme conservation call – not just last-minute emails and texts – could have reduced the supply–demand gap substantially, enabling rotating outages, while relieving supply to catch up." [35].

Demand response (DR), in which consumers either automatically or manually decrease or shift when they use energy in response to a request from the grid operator or utility, can be used as a powerful tool for load reduction during a crisis. Most DR programs within Texas currently focus on incentivizing load reduction during summer peak periods, and many are only available for commercial and industrial customers [59]. Because the residential sector in Texas consumes more electricity than the commercial sector [60], it presents a ripe opportunity for demand flexibility. Increasing participation in these programs and coherent, consistent communications rather than relying on a few text messages, emails, and tweets here or there [61] urging customers to conserve energy could decrease the need for brute-force power cuts to distribution substations.

4.5. The value of regional transmission connections

ERCOT avoids some federal regulation by being self-contained in Texas with limited connections to other states. Imported power would not have fully compensated for the loss of production inside Texas, but it's possible that a few GW of additional capacity would have blunted the worst outcomes at the depth of the crisis, giving enough spare capacity to facilitate rotating outages instead of controlled outages and giving more cushion from the moments when the entire grid almost collapsed. It is worth examining whether additional regional interconnections could potentially compensate for production shortfalls in the state and enhance the system's overall resilience. Most of the time, Texas would likely be able to sell excess power from its rapidly growing renewables capacity to other states, which implies that there might be significant economic benefits to interconnection along with resilience benefits.

Several cities in Texas, such as El Paso in the West and Beaumont in the East, suffered little or no power outages during the 2021 freeze in part because they are not part of ERCOT and are connected to other grids. El Paso also had invested in winterization which made their equipment more resilient to weather shocks [62,63].

It is not clear how much power Texas would have needed to import during the crisis to allow it to actually rotate blackouts rather than stranding some consumers without power for days. Given that some of the neighboring grids, notably the Southwest Power Pool (SPP) and Midcontinent Independent System Operator (MISO) also experienced outages, albeit less severe than ERCOT, it is not clear how much excess power could have actually been imported or whether that problem

would characterize future episodes.

Texas does have modest connections with other states to import a bit of power from Mexico (400 MW) and the Eastern United States (800 MW) through high voltage, direct-current connections, but Texas is not connected synchronously to other grids [64]. The winter seasonal assessment concluded that Texas was counting on 838 MW of imported power in its scenario planning [19].

However, some politicians are worried that increasing interconnections between Texas and other grids could lead Texas to be subject to FERC regulation. Former Texas governor and Secretary of Energy Rick Perry signaled strong opposition to such an idea, arguing that “Texans would be without electricity for longer than three days to keep the federal government out of their business.” [65]. While a number of analysts suggest that sentiment is outmoded, it may prevail given the political balance in the state [66,67].

Though synchronous connection with AC lines is likely to trigger FERC oversight of Texas power markets, DC lines do not automatically induce that outcome. Pattern Energy has a 2 GW project that is intended to link Texas to MISO through a high voltage DC line that the company claims will not affect Texas’ independent status. The company secured FERC approval in 2014 but the line hasn’t been built [68,69]. One potential compromise would be for the state to commit to NERC’s standards on reliability upgrades and some enhanced interconnections in exchange for FERC’s promise not to impose a capacity market or other major overhauls in the state’s market design [70].

5. Implications for climate change and the clean energy transition

The energy challenges facing Texas are more salient given the threat of climate change and the emergent energy transition. Though scientists are uncertain whether climate change made the freeze more likely by displacing the polar vortex southward [71], climate change has implications for Texas. Texas is especially vulnerable as it endures freezes, heat waves, droughts, floods, and windstorms. Therefore it is in Texas’ interest to prepare for a wide range of possible scenarios, including weather with hotter and colder temperatures, wetter and drier conditions, and intense winds [72]. Other localities will be under similar pressure, meaning that they have to prepare their infrastructure not for how the weather was in the 1960s but how it will be in the 2060s. Leaders in Texas have yet to demonstrate the foresight on climate change that they did with the opportunity to foster investment and profit from the nascent wind energy in the 2000s by building out transmission systems [73].

A clean energy transition that Texas helped set in motion in the wind sector is now unfolding globally. In 2011, wind provided 9% of Texas’ electricity needs but had grown to 24% by 2020 and is expected to rise to 29% in 2022. Solar is now beginning a similar rise, from 2% in 2020 and expected to climb to 9% in 2022 [74]. But, with more variable, intermittent renewable power comes new issues of grid integration and the need for firm baseload power, storage or demand response. While Texas had largely succeeded with that integration of wind in previous years with intelligent forecasting, the Texas freeze revealed that assumptions about the reliability of firm baseload power fueled by natural gas were too optimistic [13].

Getting this balance of cleanliness, affordability, and reliability right is not simply a technocratic question as it has major implications for health, equity, and human well-being. As such, the big freeze of 2021 provides a cautionary tale that others can learn from.

Declaration of Competing Interest

Joshua Rhodes and Michael Webber consult for various companies that operate in the Texas electricity market through their firm Idea-Smiths LLC. Caitlin Smith consults for various companies that operate in the Texas electricity market through her employer AB Power Advisors

LLC. Alex Gilbert is an employee of Nuclear Innovation Alliance, a non-profit think focused on advanced reactor commercialization for climate mitigation. The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

- [1] C. Pollock, “Gov. Greg Abbott says power is almost fully restored statewide and grocery stores will soon be restocked,” *The Texas Tribune*, Feb. 21, 2021. <https://www.texastribune.org/2021/02/21/texas-power-outage-grocery-stores-greg-abbott/> (accessed Mar. 17, 2021).
- [2] A. McNamara, “Over 14 million Texans are still without safe water as officials grapple with crisis,” *CBS News*, Feb. 20, 2021. <https://www.cbsnews.com/news/texas-boil-water-notices-winter-storm/> (accessed Mar. 05, 2021).
- [3] S. Mulcahy, “At least 111 people died in Texas during winter storm, most from hypothermia,” *The Texas Tribune*, Mar. 25, 2021. <https://www.texastribune.org/2021/03/25/texas-deaths-winter-storm/> (accessed Mar. 26, 2021).
- [4] M. Puleo, “Damages from Feb. winter storms could be as high as \$155 billion,” *AccuWeather*, Mar. 05, 2021. <https://www.accuweather.com/en/winter-weather/damages-from-feb-snowstorms-could-be-as-high-as-155b/909620> (accessed Mar. 19, 2021).
- [5] M. Hogan, “A Hearty Bowl of Texas Soup: How ERCOT Keeps the Lights On,” *Regulatory Assistance Project*, Oct. 23, 2019. <https://www.raponline.org/blog/a-hearty-bowl-of-texas-soup-how-ercot-keeps-the-lights-on/> (accessed Mar. 18, 2021).
- [6] K.-E. Stromström, “ERCOT’s Wild Summer Is Over. Solar Looks Like the Winner,” *Greentech Media*, Sep. 24, 2019. <https://www.greentechmedia.com/articles/read/ercots-wild-summer-is-over-solar-looks-like-the-winner> (accessed Mar. 18, 2021).
- [7] U.S. Energy Information Administration (EIA), “Texas natural gas production fell by almost half during recent cold snap - Today in Energy,” Feb. 25, 2021. <https://www.eia.gov/todayinenergy/detail.php?id=46896> (accessed Mar. 17, 2021).
- [8] ERCOT, “ERCOT calls for rotating outages as extreme winter weather forces generating units offline,” Feb. 15, 2021. <http://www.ercot.com/news/releases/show/225210> (accessed Mar. 17, 2021).
- [9] C. Traywick, M. Chediak, N. S. Malik, J. Saul, “The Two Hours That Nearly Destroyed Texas’ Electric Grid,” *Bloomberg.com*, Feb. 20, 2021.
- [10] M. Webber, “What happened in Texas is only the beginning,” *TheHill*, Mar. 01, 2021. <https://thehill.com/opinion/energy-environment/540941-what-happened-in-texas-is-only-the-beginning> (accessed Mar. 05, 2021).
- [11] D. Titley, “Texas cold snap was not ‘unprecedented,’ and it was inexcusable to be unprepared,” *Washington Post*, Feb. 22, 2021.
- [12] J. Doss-Gollin, D. J. Farnham, U. Lall, V. Modi, “How unprecedented was the February 2021 Texas cold snap?,” pre-print, Feb. 2021, Accessed: Mar. 15, 2021. [Online]. Available: <https://eartharxiv.org/repository/view/2122/>.
- [13] J. Jenkins, “Testimony of Dr. Jesse D. Jenkins, House Committee on Science, Space and Technology,” Mar. 18, 2021. <https://science.house.gov/download/jenkins-testimony> (accessed Mar. 19, 2021).
- [14] S. Stein, “Biden’s slow start,” *POLITICO*, Feb. 23, 2021. <https://politi.co/3klWf6L> (accessed Mar. 17, 2021).
- [15] Brian Bartholomew, “ERCOT expected 14GW of power plant outages in its ‘extreme’ winter planning scenario. By late Monday morning, more than 30GW were offline. <https://t.co/6HvkEaT1en>,” Feb. 24, 2021. <https://twitter.com/BPBartholomew/status/1364446059028750337> (accessed Mar. 17, 2021).
- [16] ERCOT, “Fuel Mix Report, 2020,” Mar. 09, 2021. http://www.ercot.com/content/wcm/lists/181766/FuelMixReport_PreviousYears.zip.
- [17] E. Douglas, “Texas largely relies on natural gas for power. It wasn’t ready for the extreme cold,” *The Texas Tribune*, Feb. 16, 2021. <https://www.texastribune.org/2021/02/16/natural-gas-power-storm/> (accessed Mar. 17, 2021).
- [18] A. Gilbert and M. Bazilian, “The Texas electricity crisis and the energy transition,” *Utility Dive*, Feb. 19, 2021. <https://www.utilitydive.com/news/the-texas-electricity-crisis-and-the-energy-transition/595315/> (accessed Mar. 05, 2021).
- [19] ERCOT, “Seasonal assessments show sufficient generation for winter and spring,” Nov. 05, 2020. <http://www.ercot.com/news/releases/show/216844> (accessed Mar. 17, 2021).
- [20] J. Siegel, “How and why a nuclear reactor shut down in Texas cold snap when energy was needed most,” *Washington Examiner*, Feb. 17, 2021. <https://www.washingtonexaminer.com/policy/energy/how-and-why-a-nuclear-reactor-shut-down-in-texas-cold-snap-when-energy-was-needed-most> (accessed Mar. 18, 2021).

- [21] Nuclear Regulatory Commission, "Event Notification Report For Day," NRC Web, Feb. 15, 2021. <https://www.nrc.gov/reading-rm/doc-collections/event-status/eventby/2021/20210216en.html> (accessed Mar. 18, 2021).
- [22] M. McAuliffe, "Texas nuclear unit returns to service after outage related to cold weather" S&P Global Platts, Feb. 18, 2021. <https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/021821-texas-nuclear-unit-returns-to-service-after-outage-related-to-cold-weather> (accessed Mar. 28, 2021).
- [23] U.S. Energy Information Administration (EIA), "Which states consume and produce the most natural gas?," Oct. 19, 2020. <https://www.eia.gov/tools/faqs/faq.php> (accessed Mar. 26, 2021).
- [24] A. Zelinski, "What Went Wrong With Texas's Main Electric Grid and Could It Have Been Prevented?," Texas Monthly, Feb. 17, 2021. <https://www.texasmonthly.com/news-politics/what-went-wrong-with-texas-main-electric-grid-and-could-it-have-been-prevented/> (accessed Mar. 18, 2021).
- [25] R. Adams-Heard, J. Blas, M. Chediak, "A Giant Flaw in Texas Blackouts: It Cut Power to Gas Supplies," Bloomberg.com, Feb. 19, 2021.
- [26] A. Ravikumar, "Thread on Natural Gas Failures," Twitter, Feb. 15, 2021. <https://twitter.com/arvindpawan1/status/1363254757423513603> (accessed Mar. 05, 2021).
- [27] B. Storrow, "Why the Deep Freeze Caused Texas to Lose Power," E&E News, Feb. 18, 2021. <https://www.scientificamerican.com/article/why-the-deep-freeze-caused-texas-to-lose-power/> (accessed Mar. 18, 2021).
- [28] J. Root, E. Dexheimer, J. Blackman, "This simple paperwork blunder left Texans cold during the deadly freeze," Houston Chronicle, Mar. 17, 2021. <https://www.houstonchronicle.com/business/article/Simple-paperwork-blunder-Texans-cold-winter-storm-16032163.php> (accessed Mar. 17, 2021).
- [29] E. Douglas, "Paperwork failures worsened Texas blackouts, sparking mid-storm scramble to restore critical fuel supply," The Texas Tribune, Mar. 18, 2021. <https://www.texastribune.org/2021/03/18/texas-winter-storm-blackouts-paperwork/> (accessed Mar. 18, 2021).
- [30] M. O'Shea, R. Goel, R. Miller, "Breaking down the Texas winter blackouts: what went wrong?," Wood Mackenzie, Mar. 19, 2021. <https://www.woodmac.com/news/editorial/Breaking-down-the-texas-winter-blackouts/full-report/> (accessed Mar. 18, 2021).
- [31] J. St. John, "Texas Energy System Faces a Winter Reckoning," Greentech Media, Mar. 16, 2021. <https://www.greentechmedia.com/articles/read/texas-energy-system-faces-a-winter-reckoning> (accessed Mar. 18, 2021).
- [32] A. Drane, "ERCOT was minutes from a 'black start' that would have killed power, cell signals in Texas for weeks," Houston Chronicle, Feb. 24, 2021. <https://www.houstonchronicle.com/business/article/ERCOT-holds-urgent-meeting-on-power-grid-failure-15975585.php> (accessed Mar. 18, 2021).
- [33] C. Flores, "ERCOT: Texas was minutes away from grid crash, 'black start,'" KEYE, Feb. 24, 2021. <https://cbsaustin.com/news/local/ercot-holding-emergency-board-meeting-to-discuss-grids-power-failures> (accessed Mar. 18, 2021).
- [34] B. Magnus, "Review of February 2021 Extreme Cold Weather Event – ERCOT Presentation," ERCOT, Feb. 24, 2021. http://www.ercot.com/content/wcm/key_documents/lists/225373/2.2_REVISED_ERCOT_Presentation.pdf.
- [35] V. Rai, "Testimony before US House of Representatives Committee on Science, Space, and Technology," Mar. 18, 2021. <https://science.house.gov/hearings/lessons-learned-from-the-texas-blackouts-research-needs-for-a-secure-and-resilient-grid> (accessed Mar. 18, 2021).
- [36] TEPRI, "Blog – Lived Experiences of Winter Storm Uri," Texas Energy Poverty Research Institute, Mar. 17, 2021. <https://txenergypoverty.org/2021/03/blog-lived-experiences-of-winter-storm-uri/> (accessed Mar. 18, 2021).
- [37] A. Skibell, M. Lee, "Utility data reveals uneven toll of Texas blackouts," E&E News, Mar. 26, 2021. <https://www.eenews.net/stories/1063728551> (accessed Mar. 26, 2021).
- [38] A. Ura, J. P. Garnham, "Already hit hard by pandemic, Black and Hispanic communities suffer the blows of an unforgiving winter storm," The Texas Tribune, Feb. 19, 2021. <https://www.texastribune.org/2021/02/19/Texas-winter-storm-suffering-inequities/> (accessed Mar. 18, 2021).
- [39] E. Trovati, L. Vasquez, "Racial Inequities Emerge As Houston Recovers From Last Week's Winter Storm," Houston Public Media, Feb. 22, 2021. <https://www.houstonpublicmedia.org/articles/news/weather/2021/02/22/391862/as-houston-area-folks-recover-from-the-winter-storm-racial-inequities-emerge/> (accessed Mar. 18, 2021).
- [40] A. Schneider, "U.S. Government Prepared To Act On Texas Grid Changes, FERC Chief Warns," Houston Public Media, Mar. 04, 2021. <https://www.houstonpublicmedia.org/articles/news/energy-environment/2021/03/04/392895/ferc-chief-warns-orders-to-weatherize-texas-grid-on-the-way/> (accessed Mar. 18, 2021).
- [41] C. Morehouse, "Congress, Texas should 'rethink' ERCOT's 'go it alone approach': FERC Chair Glick," Utility Dive, Feb. 19, 2021. <https://www.utilitydive.com/news/congress-texas-should-rethink-ercots-go-it-alone-approach-ferc-chair/595335/> (accessed Mar. 18, 2021).
- [42] NRG, "What Texas Businesses Need to Know about Scarcity Pricing this Summer," NRG Energy. <https://www.nrg.com/insights/energy-education/what-texas-businesses-need-to-know-about-scarcity-pricing-this-s.html> (accessed Mar. 19, 2021).
- [43] T. McLaughlin, "Texas wholesale electric prices spike more than 10,000% amid outages," Reuters, Feb. 15, 2021.
- [44] R. Gold, K. Blunt, "Amid Blackouts, Texas Scrapped Its Power Market and Raised Prices. It Didn't Work," Wall Street Journal, Feb. 25, 2021.
- [45] R. Surendran, W. W. Hogan, H. Hui, C.-N. Yu, "Scarcity Pricing in ERCOT," Jun. 2016. [Online]. Available: https://cms.ferc.gov/sites/default/files/2020-05/20160629114652-3%2520-%2520FERC2016_Scarcity%2520Pricing_ERCOT_Resmi%2520Surendran.pdf.
- [46] N. S. Malik, "Texas Watchdog Says Grid Operator Made \$16 Billion Error - Bloomberg," Bloomberg, Mar. 04, 2021. <https://www.bloomberg.com/news/articles/2021-03-04/texas-watchdog-says-power-grid-operator-made-16-billion-error?sref=Os5mORbE> (accessed Mar. 05, 2021).
- [47] Reuters, "Texas House leader signals opposition to retroactive power price cuts," Reuters, Mar. 17, 2021.
- [48] G. Hering, J. Horwath, "ERCOT market monitor cuts storm pricing error estimate to \$3.2 billion from \$16 billion," SPBGlobal, Mar. 11, 2021. <https://www.spglobal.com/platts/en/market-insights/latest-news/electric-power/031121-ercot-market-monitor-cuts-storm-pricing-error-estimate-from-16-bil-to-32-bil> (accessed Mar. 19, 2021).
- [49] E. Dearman, "What would reversing \$16 billion from winter storm mean for Texans' electricity bills?," Fort Worth Star-Telegram, Mar. 18, 2021. <https://www.star-telegram.com/news/politics-government/article249987264.html> (accessed Mar. 19, 2021).
- [50] FERC and NERC, "Report on Outages and Curtailments During the Southwest Cold Weather Event of February 1-5, 2011," 2011. [Online]. Available: <https://www.ferc.gov/sites/default/files/2020-04/08-16-11-report.pdf>.
- [51] U.S. Energy Information Administration (EIA), "US Oil and Gas Wells by Production Rate," Dec. 23, 2020. <https://www.eia.gov/petroleum/wells/index.php> (accessed Mar. 26, 2021).
- [52] K. Fox, "Records show dozens of power plants repeated 2011 failures," ABC13 Houston, Mar. 06, 2021. <https://abc13.com/10393754/> (accessed Mar. 20, 2021).
- [53] N. Satija, A. Gregg, "Ten years ago, 241 Texas power plants couldn't take the cold. Dozens of them failed again this year.," Washington Post, Mar. 06, 2021.
- [54] R. T. Garrett, A. Morris, "House panel OKs storm bills to require weatherizing Texas power plants, revamping grid management," Dallas Morning News, Mar. 18, 2021. <https://www.dallasnews.com/news/politics/2021/03/19/house-panel-oks-storm-bills-to-require-weatherizing-texas-power-plants-revamping-grid-management/> (accessed Mar. 19, 2021).
- [55] R. T. Garrett, J. Barragán, "House speaker pushes using Texas savings, Biden relief money to help weatherproof power plants," Dallas Morning News, Mar. 11, 2021. <https://www.dallasnews.com/news/politics/2021/03/12/house-speaker-pushes-using-texas-savings-biden-relief-money-to-pay-for-power-plant-weather-proofing/> (accessed Mar. 19, 2021).
- [56] C. Fortuna, "Houston Chronicle Says Texas Failed To Build In Energy Efficiency To Plan For Climate Extremes," CleanTechnica, Feb. 28, 2021. <https://cleantechnica.com/2021/02/28/houston-chronicle-says-texas-failed-to-build-in-energy-efficiency-to-plan-for-climate-extremes/> (accessed Mar. 26, 2021).
- [57] J. Matson, S. Ayyagari, "Efficient, Resilient Buildings Can Help Texas Weather the Next Crisis," RMI, Mar. 25, 2021. <https://rmi.org/efficient-resilient-buildings-can-help-texas-weather-the-next-crisis/> (accessed Mar. 26, 2021).
- [58] S. Nadel, "Texas Blackouts Offer Lesson For Reducing Energy Demand Spikes," Feb. 22, 2021. <https://www.aceee.org/blog-post/2021/02/texas-blackouts-offer-lesson-reducing-dangerous-spikes-energy-demand> (accessed Mar. 26, 2021).
- [59] Austin Energy, "Automated Demand Response (ADR) Technical Guide," May 2020. [Online]. Available: https://austinenrg.com/wcm/connect/48413f11-d704-43fb-be8e-31c663c1a88d/Automated-Demand-Response-Technical-Guide.pdf?MOD=AJPERES&CONVERT_TO=url&CACHEID=ROOTWORKSPACE-48413f11-d704-43fb-be8e-31c663c1a88d-n7R3u4E.
- [60] A. Stillwell, C. King, M. Webber, I. Duncan, A. Hardberger, The energy-water Nexus in Texas, Ecol. Soc. 16 (1) (2011), <https://doi.org/10.5751/ES-03781-160102>.
- [61] ERCOT, "ERCOT on Twitter," Twitter, Feb. 15, 2021. https://twitter.com/ERCOT_ISO/status/1361211669788176384 (accessed Mar. 19, 2021).
- [62] S. Juarez, "El Paso Heeded the Warnings and Avoided a Winter Catastrophe," Texas Monthly, Feb. 19, 2021. <https://www.texasmonthly.com/news-politics/el-paso-electric-winter-storm-2021/> (accessed Mar. 19, 2021).
- [63] J. Rogalski, "Texas counties with fewer power outages are not part of state grid," KHOU, Feb. 17, 2021. <https://www.khou.com/article/news/investigations/texas-power-outage-counties-with-fewer-power-outages-are-not-part-of-state-grid/285-67277280-7fce-42ca-b55b-f8fc639c0889> (accessed Mar. 19, 2021).
- [64] J. St. John, "Looking for Fixes to What Broke the Texas Power Grid," Greentech Media, Feb. 22, 2021. <https://www.greentechmedia.com/squared/dispatches-from-the-grid-edge/looking-for-fixes-to-what-broke-the-texas-power-grid> (accessed Mar. 19, 2021).
- [65] J. Osborne, "To ire of many, Perry claims Texans would suffer blackouts to avoid feds," Houston Chronicle, Feb. 17, 2021. <https://www.houstonchronicle.com/business/energy/article/Perry-says-Texans-willing-to-suffer-blackouts-to-15956705.php> (accessed Mar. 19, 2021).
- [66] M. E. Webber, "Texas' power grid should diversify," Waco Tribune, Mar. 05, 2021. https://wacotrib.com/opinion/columnists/michael-webber-texas-power-grid-should-diversify/article_43ac5a04-7de2-11eb-b21a-3727f1f61c06.html (accessed Mar. 26, 2021).
- [67] Reuters, "Texas will have to winterize its grid or interconnect with neighbors: experts," Reuters, Mar. 04, 2021.
- [68] G. Meyer, "US power line tensions grow over green energy surge," Financial Times, Feb. 18, 2021. <https://www.ft.com/content/1742140f-5dd6-4808-8ad7-526404482058> (accessed Mar. 19, 2021).
- [69] H. K. Trabish, "Texas must increase ties to the national grid and DER to avoid another power catastrophe, analysts say," Utility Dive, Mar. 02, 2021. <https://www.utilitydive.com/news/texas-must-increase-ties-to-the-national-grid-and-der-to-avoid-another-powe/595845/> (accessed Mar. 19, 2021).
- [70] D. Roberts, "Lessons from the Texas mess," Volts, Feb. 24, 2021. <https://www.volts.wtf/> (accessed Mar. 19, 2021).

- [71] A. Dessler, "Tweet," Twitter, Feb. 23, 2021. <https://twitter.com/AndrewDessler/status/1364094069438177281> (accessed Mar. 19, 2021).
- [72] Niskanen Center, "Understanding the Texas blackouts: What lessons can we learn?," Niskanen Center, Mar. 01, 2021. <https://www.niskanencenter.org/event-understanding-the-texas-blackouts-what-lessons-can-we-learn/> (accessed Mar. 19, 2021).
- [73] A. Orrell, J. Homer, S. Bender, M. Weimar, "Energy Policy Case Study – Texas: Wind, Markets, and Grid Modernization," Pacific Northwest National Laboratory, 2016. [Online]. Available: https://www.pnnl.gov/main/publications/external/technical_reports/PNNL-25822.pdf.
- [74] Energy News, "Texas Electricity Trends for 2021," ElectricityPlans, Jan. 27, 2021. <https://electricityplans.com/texas-electricity-trends-for-2021/> (accessed Mar. 19, 2021).
- [75] Blake Shaffer, "Tweet", Feb. 24, 2021. <https://twitter.com/bcshaffer/status/1364635625907912705> (accessed Mar. 17, 2021).
- [76] W. Christian, "Texas' Blackouts Blew In on the Wind", Wall Street Journal, Mar. 19, 2021. Accessed: May 03, 2021. [Online]. Available: <https://www.wsj.com/articles/texas-blackouts-blew-in-on-the-wind-11616192622>.
- [77] N. Satija and A. Gregg, "Texas' chief energy regulator fiercely defended fossil fuels after historic blackouts. She also profits from oil and gas," The Texas Tribune, Mar. 19, 2021. <https://www.texastribune.org/2021/03/19/texas-blackouts-christi-craddick-railroad-commission-oil-gas/> (accessed May 03, 2021).
- [78] M. Farmer, "Third energy firm declares bankruptcy in Texas snow storm fallout", Power Technology, Mar. 16, 2021. <https://www.power-technology.com/news/industry-news/texas-snow-storm-bankrupt-fallout-energy-prices-ercot/> (accessed May 04, 2021).
- [79] J. Hill and A. Monahan, "Brilliant Energy Files for Bankruptcy After Texas Power Crisis," Bloomberg, Mar. 17, 2021. <https://www.bloombergquint.com/business/brilliant-energy-files-for-bankruptcy-after-texas-power-crisis> (accessed May 04, 2021).
- [80] Reuters, "Texas freeze delivers billions in profits to gas and power sellers", Reuters, May 06, 2021. <https://www.reuters.com/business/energy/results-tally-up-billions-profit-texas-freeze-gas-power-sellers-2021-05-06/> (accessed Jun. 03, 2021).