ANL-21/29

Feb. 2021 Electricity Blackouts and Natural Gas Shortages in Texas

Preliminary Analysis of Texas 2021 Power Outages

Energy Systems Division
Nuclear Science and Engineering Division

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Preliminary Analysis of Texas 2021 Power Outages

W. Neal Mann[1], Katie Biegel[2], Nicolas E. Stauff[2], Brent Dixon[3]
[1] Energy Systems Division, Argonne National Laboratory
[2] Nuclear Science and Engineering Division, Argonne National Laboratory
[3] Idaho National Laboratory

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EXECUTIVE ABSTRACT

Event and Aftermath

An extreme winter storm and extended cold weather event hit Texas and the central United States February 8–19, 2021. This led to both exceptional energy demands and issues with electricity and natural gas supplies over several days. Residential space heating drove the increases in demand, with over 60% of Texas homes using electric heat pumps and 35% using natural gas furnaces. Supply issues were caused by freezing equipment and supply lines, impacting both natural gas supplies and most forms of electricity generation. [1] Natural gas supplies were especially important because natural gas also supplied about 50% of the electricity generating capacity in ERCOT, the primary grid operator in Texas. [2] Due to the supply shortages, wholesale electricity prices were forced to the ERCOT maximum of $9,000/MWh for over three days (recent range $20–40/MWh), [3] and natural gas prices for physical delivery exceeded $400/MMBtu in some areas (recent range $3–4/MMBtu). [4]

A large number of generators had been forced offline by the cold weather by Feb. 14, setting the stage for the generation shortages. At the beginning of the emergency, about 15 GW of wind capacity, 12 GW of natural gas capacity, 2 GW of coal capacity, and several hundred MW of solar PV capacity was unavailable due to outages. [5] On Feb. 15, just after midnight, the rapid drop in temperatures state-wide forced off-line an additional 10 GW of natural gas capacity, 2 GW of coal capacity, and 2 GW of wind capacity in a matter of hours. This generation shortfall led to emergency load shedding beginning 01:23. Additional plants dropped offline as the cold weather spread eastward to the Gulf Coast. At 05:26, one nuclear reactor tripped offline, removing about 1.3 GW of capacity. [6], [7]

ERCOT forced 10–20 GW of load offline Feb. 15–17 to prevent a system-wide blackout. The unusually cold weather led to the loss of over 40% of Texas natural gas production capacity and over 50% of ERCOT electricity generation capacity, about 50 GW. [4], [5] Natural gas production stopped at many wells due to frozen water in the gas lines, while half of the electric generators were affected by frozen pipes, valves, instrumentation, or other equipment. On Feb. 17, 10 GW of capacity was brought back online, and ERCOT ceased load shedding just before midnight. Warmer temperatures in some areas on Feb. 19 reduced heating-related loads, and enough generators were back online for ERCOT to end emergency operations.

Coal, natural gas, and nuclear generators were forced offline to varying degrees due to the freezing weather. A common cause of these outages was frozen plant equipment, since many Texas power plants were not designed to operate in subfreezing conditions and low wind chills for several days. For example, Unit 1 of the South Texas Project nuclear power plant tripped offline for nearly two days starting Feb. 15, not returning to full power until Feb. 18 due to the “failure of a feedwater pressure sensing line” sending a false signal. [7], [8] Natural gas-fired generators also experienced natural gas supply shortages, leading to deratings and outages. [4]

Wind and solar PV also experienced significant outages. [5] Over half of the wind capacity was already forced offline at the start of the generating emergency, with some additional capacity lost on Feb. 15. It is likely that these outages were caused by frozen turbine components or blade icing. Solar PV generation is a small but growing portion of the ERCOT generating mix, but it also underperformed during the emergency. Solar PV outages might have been caused by frozen equipment or snow obscuring panels, but this has not been officially confirmed.

The ERCOT grid has very limited interconnections with the Eastern Interconnection (via the Southwest Power Pool) and Mexico (via CENACE). [9] Both adjacent markets were unable to supply emergency power due to their own related operational issues. Even if they had been available to assist, the ties were too small to overcome a 20 GW generating deficit.

Preliminary Analysis

The Feb. 2021 cold weather event and energy system failures are extremely similar to cold weather events in Jan. 2014, Feb. 2011, and Dec. 1989. [10]–[12] Many of the recommendations from the primary post-event reports still apply, but they have only been partially implemented, based on performance during these events.

Most Texas power plants were not originally designed to operate under prolonged cold, [13] and critical plant components like instrumentation, valves, and piping are susceptible to freezing. Likewise, natural gas production and processing systems can be degraded in cold weather due to freezing of produced water in pipelines. This event illustrated the intertwined risks of heating and electricity shortages when natural gas supplies are limited.

Wind turbines and solar PV panels are also susceptible to derates and outages during cold weather events. If capacity growth continues, their effects on bulk power system reliability will increase. In future decarbonized electricity markets, a variety of zero-carbon energy sources would reduce the impact of a single energy source outage in an extreme weather event.

Energy storage systems are a very small but growing part of the ERCOT grid. Any existing and new energy storage technology should be designed to the same level of cold-weather performance as other power plant types.

Relevance to Nuclear Power Plants

South Texas Project Unit 1 was forced offline Feb. 15–17 due to cold weather. [7] The unit had experienced a similar forced outage during a Dec. 1989 cold weather event. [12] The other nuclear power units in ERCOT were unaffected by the weather (South Texas Project Unit 2, Comanche Peak Units 1 and 2). A small number of nuclear power plants in the U.S. have partially-exposed steam turbines and other equipment, including South Texas Project and Comanche Peak. Weather protection of sensors and associated small diameter pipes/tubes in the balance of plant should be considered, as these components have been problematic for thermal power plants in past cold weather events. [12], [14]

Nuclear power plants are not susceptible to sudden fuel supply interruptions like existing natural gas power plants, so additional nuclear capacity would reduce these system-wide risks. New nuclear power plants should be designed for extreme hot and cold weather operations without derating, and the range of future risks due to climate change should be incorporated into the designs.

Distributed or portable nuclear power plants currently under development could be useful for emergency power generation in the future. For weather-related disasters, these would be most helpful if staged beforehand. For the Feb. 2021 weather event, major roads were impassible for several days, but weather forecasts suggested a major cold weather event two weeks in advance.

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1 Cold Weather Event Description

Starting on Feb. 4, 2021, a major cold weather outbreak began in Montana and North Dakota, and pushed south to the Gulf Coast over the next two weeks. [15], [16] It was caused by an intrusion of the artic polar vortex much farther south than usual, associated with a negative Arctic Oscillation Index. [17] Daily high and low temperatures in Amarillo began to drop on Feb. 8, declining to a nadir on Feb. 15. [18] An associated winter storm brought unusually large amounts of snow and ice to Texas starting Feb. 14, with temperatures 20 to 30 °F below normal. All-time record lows were matched or beaten across the region on Feb. 16. [19] Temperatures statewide increased rapidly Feb. 19–20, with all areas of the state above freezing by Feb. 21. [15] For the week ending Feb. 20, 2021, the south-central United States[1] experienced an average temperature of 22 °F, nearly 25 °F below the 1981–2010 base period (Figure 1). [20]

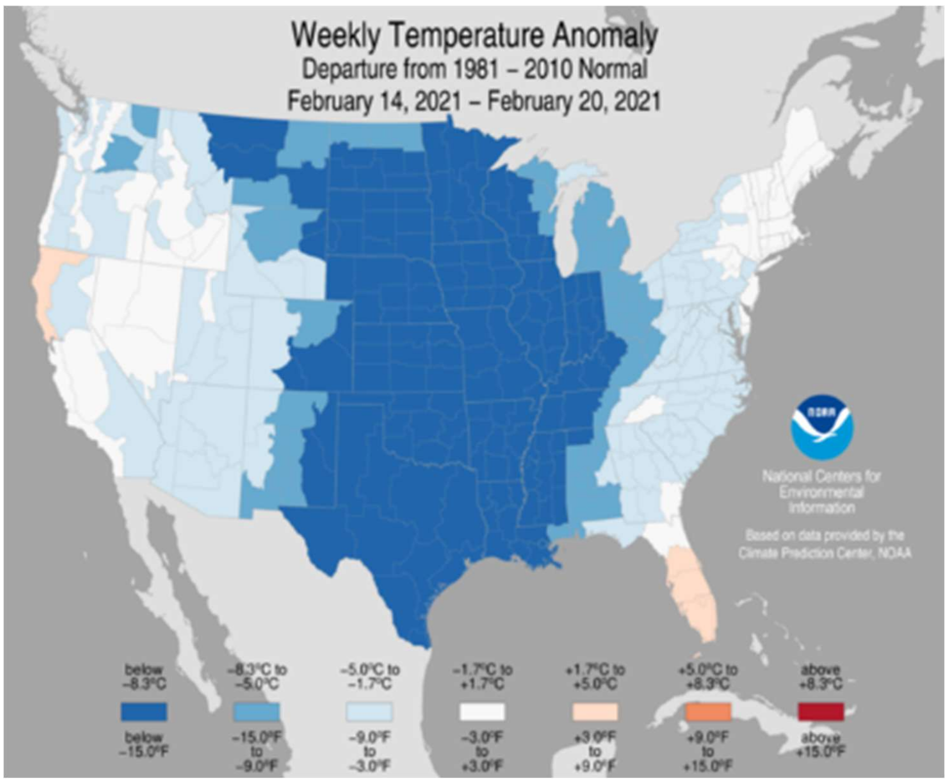

Figure 1. Weekly temperature anomaly for the week ending Feb. 20, 2021. [20]

2 Emergency Rolling Blackouts and Natural Gas Shortages

The sudden drop in air temperatures led to rapid increases in demand for both electricity and natural gas. In Texas, almost all residential space heating is done with electric heat pumps (61%) or natural gas furnaces (35%). [1] During an extreme cold weather event, both electricity and natural gas supplies can be strained, especially since over 50% of generating capacity is natural gas-fired in ERCOT, the primary grid operator in Texas. [2]

1 The NOAA National Centers for Environmental Information defines the South climate region as Arkansas, Kansas, Louisiana, Mississippi, Oklahoma, and Texas.

ERCOT resorted to emergency rotating outages on Feb. 15 at 01:25 CST. Over 30 GW of generation capacity had been forced offline, leading ERCOT to order a 10 GW load reduction. [21] This was necessary to prevent a system-wide blackout. [22] By Feb. 17, over 46 GW of generation capacity was offline, including 28 GW of thermal power plants and 18 GW of wind and solar PV. [23] Generation and load outages continued until Feb. 19, when temperatures rose significantly and all load was allowed to be reconnected. There was still over 34 GW of offline generation the morning of Feb. 19. [24] Figure 2 shows the large gap between the forecast demand and available generation during the cold weather event.

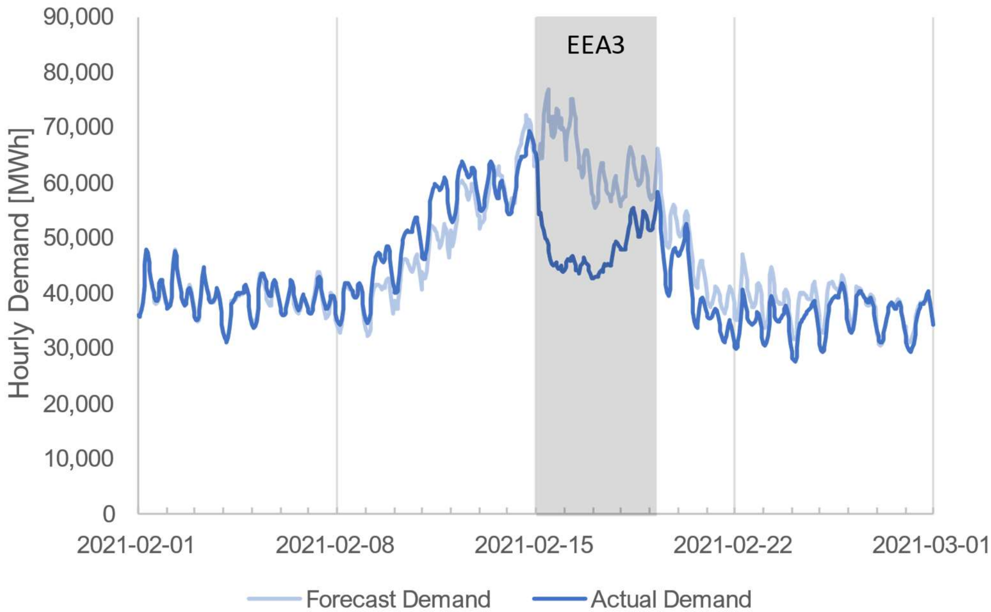

Figure 2. ERCOT hourly electricity demand, generation, and interchange during the Feb. 2021 cold weather event. [25] Energy Emergency Alert Level 3 (EEA3) is shown in the grey box, active Feb. 15 01:20 until Feb. 19 09:00 CST.

Rolling blackouts turned into extended outages in some areas. ERCOT ordered the transmission and distribution service providers (TDSP) to shed proportional amounts of load. Each TDSP has discretion on how to enact those orders, so some circuits were prioritized for critical loads like hospital and public safety facilities. [26] There were no reports of major transmission line outages, but these are not necessarily made public.

The extended freezing temperatures in Texas also led to freeze-offs at natural gas wellheads and gathering lines, where gas flow is blocked by associated water that freezes. These conditions caused Texas natural gas production to fall over 40% in a matter of days (Figure 3). [4] Natural gas storage withdrawals for the week ending Feb. 19 (338 Bcf) were near the all-time record (359 Bcf), residential and commercial consumption was 62 Bcf/day (near all-time high), and electric power consumption set a new winter peak at 33 Bcf/day. [4]

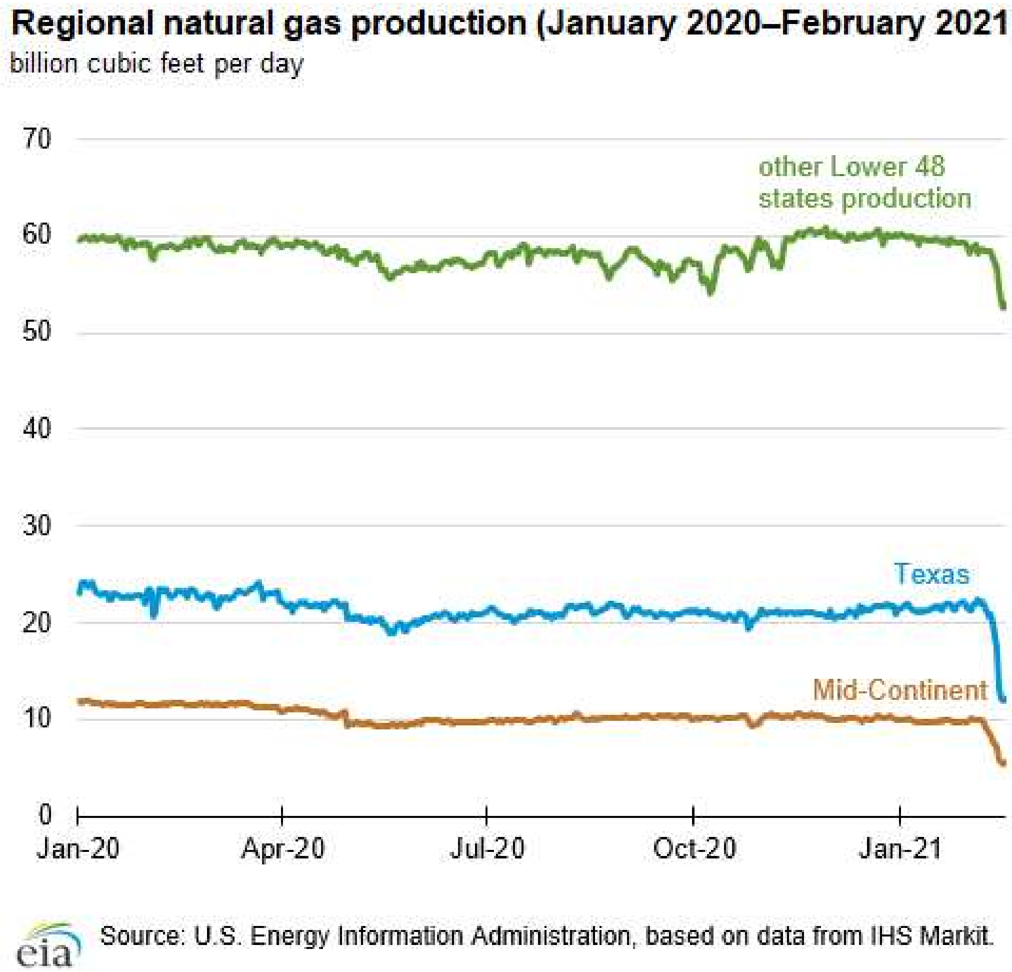

Figure 3. Regional natural gas production dropped precipitously around Feb. 15, 2021. [4]

3 Historical Texas Climate and ERCOT Demand

ERCOT is historically a "summer peaking" grid, meaning that the top load hours each year occur in the summer months of June, July, and August. The current all-time high peak load of 74.8 GW was set 12 Aug. 2019. [27] The previous all-time winter peak load was 65.9 GW on 17 Jan. 2018 [9] Because of the lower peak loads, winter maintenance outages are performed at some plants. ERCOT's planned winter peak load for 2020–21 was about 58 GW, with an extreme winter peak load forecast of 67 GW. [9]

Summertime heat in Texas tends to increase steadily through the season due to a lack of clouds. It can be punctuated by thunderstorms and hurricanes, but rapidly forming "heat domes" are rare. Conversely, winter weather is more variable, and cold fronts can move through suddenly. Importantly, extremely cold fronts happen even during mild winters. [28]

These weather trends create different load outcomes. For summer, the day-to-day peak load tends to vary only slightly, following the seasonal trend. For winter, the day-to-day peak load can suddenly increase by 20 GW or more with a strong cold front. [28]

4 Generator Disruptions by Fuel/Prime Mover

Due to the extreme cold weather, generation resources began to go offline in the second week of February (Figure 4). An early warning flag became evident in the early morning of February 9, when ERCOT began to draw down their supply of online and offline reserves in order to augment active generation capacity. By Feb. 14, there was already about 28 GW of capacity offline (out of 105 GW, ≈27%): about 15 GW of wind (out of 25 GW, ≈60%), 12 GW of natural gas (out of 55 GW, ≈22%), 2 GW of coal (out of 14 GW, ≈14%), and several hundred MW of solar PV (out of 4 GW, <10%).[2] [5], [29] These pre-event outages were primarily caused by cold weather.

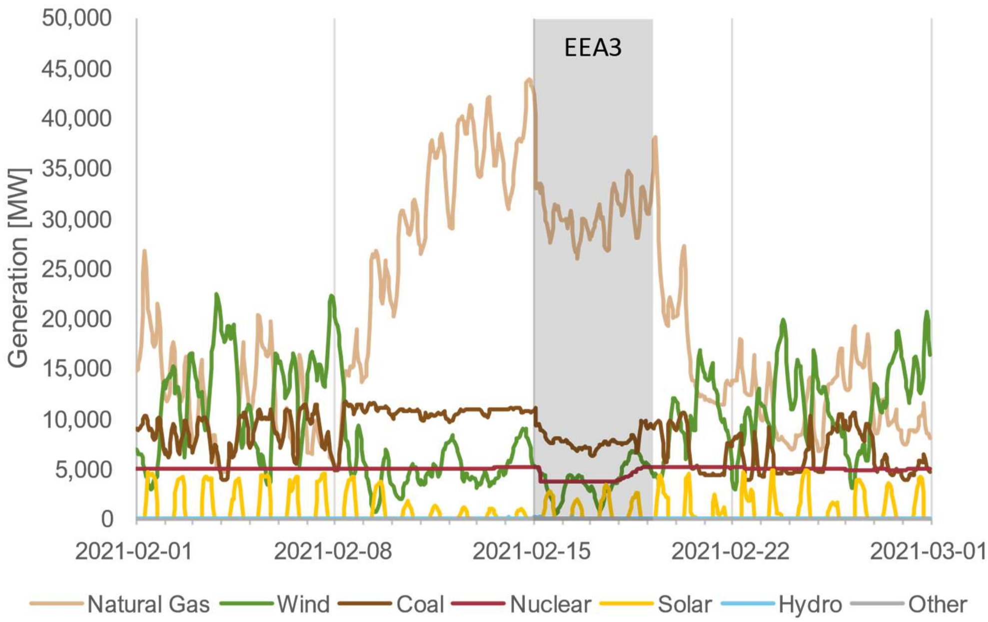

Figure 4. ERCOT hourly generation by fuel type, Feb. 2021. [25] Energy Emergency Alert Level 3 (EEA3) is shown in the grey box, active Feb. 15 01:20 until Feb. 19 09:00 CST.

Despite the increasing demand for electricity due to the severe cold, the ERCOT dispatch profile continued to show its usual daily periodicity up through February 15—peaking during the morning and early evening, reaching a minimum between 1:00 and 3:00 AM each day. [30] Between midnight and 1:23 AM on February 15, generator outages rose from 30 GW to 35 GW, triggering Energy Emergency Alert Level 3 (EEA3)[3] and 1 GW of load shed. Over the next 30 minutes, an additional 5 GW of generation was lost, and the system frequency dipped below 59.4 Hz, indicating an imminent loss of more generation without intervention. To counter this, ERCOT shed over 8 GW of load to stabilize the system frequency. [5]

The generating fleet performance aggregated by fuel type is shown in Figure 4. Typical ERCOT winter daily generation consists of variable wind and solar PV output, steady nuclear output, and load-following coal and natural gas generation (Figure 4, first and last weeks of Feb.). Starting

2 These are nameplate capacities. ERCOT's resource adequacy calculations use derated capacities for expected availability.

3 ERCOT has emergency operations procedures defined by severity, Levels 1–3. Levels 1 and 2 are usually set when reserves drop below thresholds. Level 3 is declared when reserves fall below 1,430 MW or when the system frequency falls below 59.91 Hz for 25 consecutive minutes. ERCOT will only direct load-serving entities to shed load under Level 3 conditions.

Feb. 8, wind and solar PV generation declined to new, lower averages. These reductions were made up by increases in coal and natural gas generation. Maximum coal capacity was quickly reached on Feb. 8, so natural gas generators continued to come online to meet the increasing demand for the remainder of the week. This ramp-up was interrupted by forced outages, leading to the emergency load shedding.

During the emergency outage period Feb. 14–19, a total of 356 generators experienced an outage, representing about 50% of all generation resources available in MW for the 2020–21 winter season. [5] Additional details for each fuel type's performance are given in the following sections.

4.1 Natural Gas

Natural gas-fired generators represented about 50% (55 GW) of nameplate capacity before the cold weather event. [2] As statewide temperatures began to drop on Feb. 8, natural gas-fired generation began increasing to meet demand (Figure 5). Despite 12 GW of natural gas-fired generation being unavailable on Feb. 14, close to 80% of nameplate capacity was producing that day.

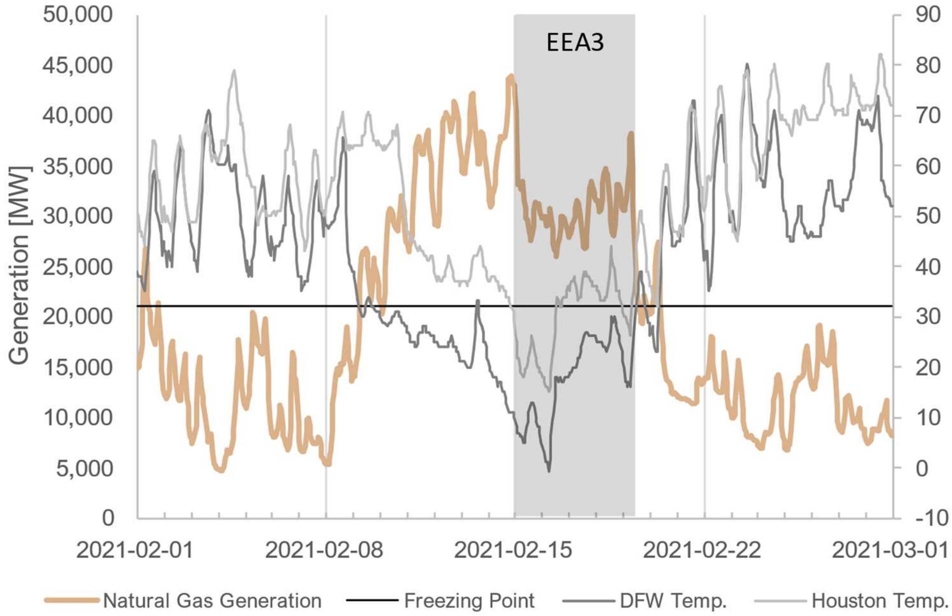

Figure 5. Natural gas-fired generation [25] and dry bulb air temperatures at Dallas/Fort Worth and Houston [18], Feb. 2021. Energy Emergency Alert Level 3 (EEA3) is shown in the grey box, active Feb. 15 01:20 until Feb. 19 09:00 CST.

A significant number of natural gas-fired generators tripped offline in the early morning hours of Feb. 15 as part of the broader cascading-outage event. Many of these generators would remain offline for several days. Frozen equipment and natural gas supply shortages both contributed to the extended forced outages.

4.2 Wind

Wind accounted for about 24% of nameplate capacity (25 GW) going into winter 2021. [29] Wind plants in ERCOT are concentrated in West Texas and the Texas Panhandle, with a smaller amount of capacity along the southern Gulf Coast and in South Texas. Despite the geographic diversity, ERCOT-wide wind generation can rise and fall dramatically. On Feb. 7, just before midnight, wind generation exceeded 22 GW (Figure 6). As the weather event commenced, wind production dropped sharply and stayed well below normal levels for 1 ½ weeks. On Feb. 14, wind generation had fallen from 9 GW to 5 GW as the grid event started, and it fell below 1 GW for several hours on Feb. 15 and Feb. 17. It would remain below 10 GW until the evening of Feb. 19. [25]

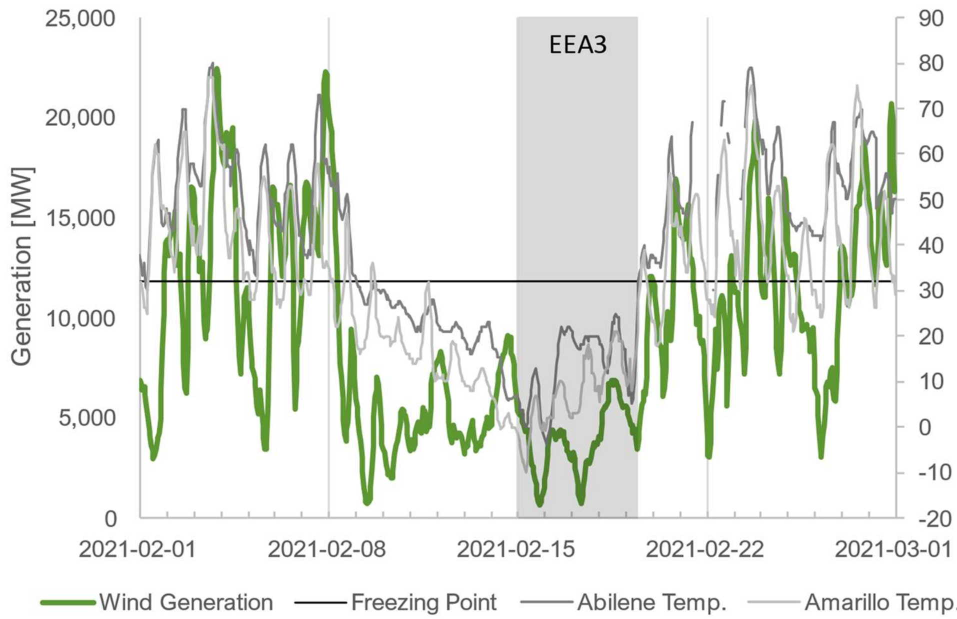

Figure 6. Wind generation [25] and dry bulb air temperatures at Abilene and Amarillo [18], Feb. 2021. Energy Emergency Alert Level 3 (EEA3) is shown in the grey box, active Feb. 15 01:20 until Feb. 19 09:00 CST.

On Feb. 14, about 15 GW of wind capacity was forced offline, rising to over 17 GW by Feb. 15. Wind outages began slowly decreasing on Feb. 18, and by Feb. 19 began sharply declining. [5] By this point, more than half of wind capacity was back online.

ERCOT assumes a worst-case 20% of nameplate wind capacity will be available for winter peaks. For the winter 2020–21, that would be about 5 GW. ERCOT-wide wind generation dipped well below this level on multiple occasions the weeks of Feb. 8 and Feb. 15. The average wind generation during the emergency outage period Feb. 15–19 was just over 4 GW. [25]

No official reports have described the causes of the wind outages. Past cold weather events in Texas and elsewhere have led to frozen turbine components and off-design operating conditions leading to forced outages. [31]

4.3 Coal

Coal made up about 13% (14 GW) of nameplate capacity in Dec. 2020. [29] During the first week of Feb. 2021, coal generation was variable as generators were dispatched up and down to meet demand. By the second week of February, about 11 GW of coal-fired generation was producing near their maximum output. [25]

Just before 2:00 AM on Feb. 15, about 2 GW of coal capacity tripped offline (Figure 7). [5] Coal generation stayed between 6 and 8 GW until Feb. 18, when it rose back to nearly 10 GW. It is unclear if generation changes during the event were due to ERCOT dispatch orders or to variable deratings and other performance problems. As with natural gas-fired generators, it is likely that coal outages were primarily caused by frozen plant components such as feedwater systems for the steam generators. However, frozen coal and conveyance equipment caused an outage at the Oak Grove power plant. [32]

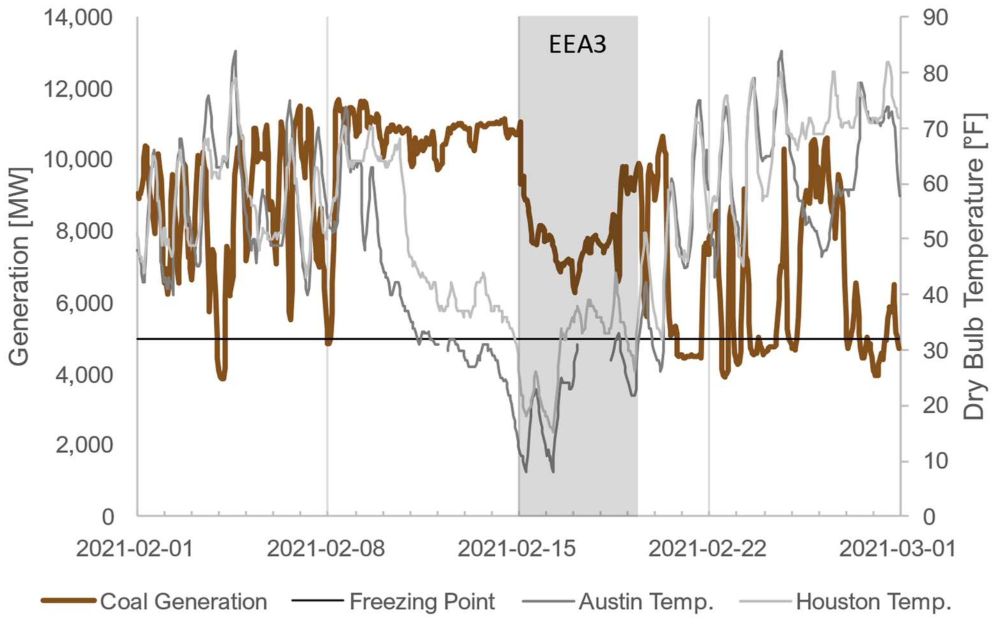

Figure 7. Coal-fired generation [25] and dry bulb air temperatures at Austin and Houston [18], Feb. 2021. Energy Emergency Alert Level 3 (EEA3) is shown in the grey box, active Feb. 15 01:20 until Feb. 19 09:00 CST.

4.4 Nuclear

Nuclear power plants provided about 5% (5 GW) of capacity in December 2020. [29] Nuclear power plants in ERCOT typically operate continuously at full power because of their position in the merit order bid stack. This was the case in the weeks leading up to the cold weather event (Figure 8). South Texas Project (STP) 1 was automatically tripped offline at 5:27 AM on Feb. 15. [6]. The weather-related “failure of a feedwater pressure sensing line” caused a false signal. [8] This resulted in the shutdown of two feedwater pumps which caused low steam generator levels, requiring the plant to go offline. [7] Unit 1 did not return to full power until Feb. 18. [7] STP 2 was unaffected. Neither unit lost offsite power.

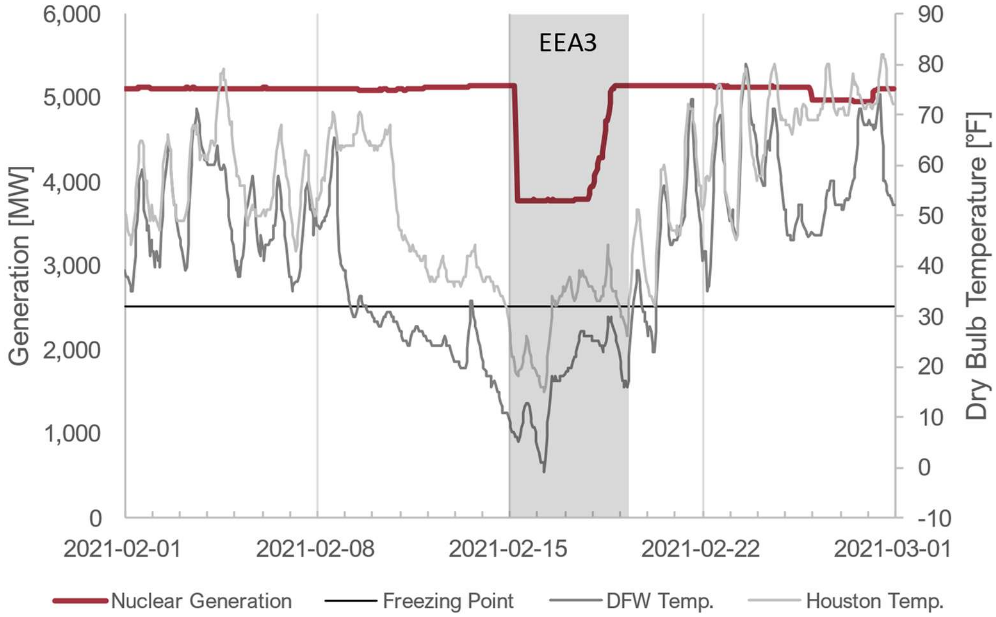

Figure 8. Nuclear generation [25] and dry bulb air temperatures at Dallas/Fort Worth and Houston [18], Feb. 2021. Energy Emergency Alert Level 3 (EEA3) is shown in the grey box, active Feb. 15 01:20 until Feb. 19 09:00 CST.

STP 1 previously tripped offline during the Dec. 1989 cold weather event. The root causes were frozen water lines, valves, and instrumentation. [12]

Two other nuclear power units in the region (but outside ERCOT) were potentially affected by the winter storm. Arkansas Nuclear 1 descended to 33% power Feb. 16–17 and did not return to full power until Feb. 19. Arkansas Nuclear 2 descended to 88% power the morning of Feb. 16 but returned to 97% power by the following day. [33] These power changes could have been intentional power reductions requested by MISO, the grid operator. [34]

Comanche Peak 1 and 2 operated at 100% power throughout the week, as did nuclear power plants in neighboring states of Kansas (Wolf Creek), Louisiana (River Bend and Waterford), and Mississippi (Grand Gulf). The River Bend Station commenced a refueling outage on Feb. 21, just days after the cold weather event ended. [35]

4.5 Solar PV

Solar PV made up about 4% (4–5 GW) of capacity before the cold weather event. [29] Solar PV generation was significantly below maximum beginning Feb. 10 (Figure 9). This was likely due to increasing cloud cover rather than outages. Some solar PV generation continued to operate during the cold weather event, with peak output between 2 and 4 GW most days. [25] About 1 GW was forced offline Feb. 15–16, with most outages over by Feb. 20. [5] ERCOT's reported forced outages were possibly due to snow or ice on panels, but this has not been officially confirmed.

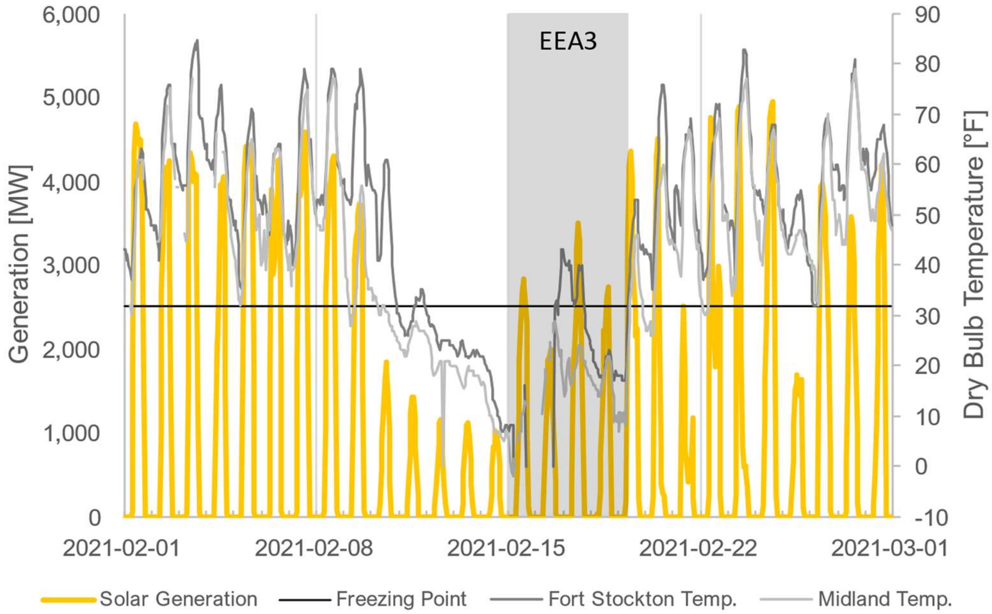

Figure 9. Solar PV generation [25] and dry bulb air temperatures at Fort Stockton and Midland [18], Feb. 2021. Energy Emergency Alert Level 3 (EEA3) is shown in the grey box, active Feb. 15 01:20 until Feb. 19 09:00 CST.

4.6 Other Generators

Hydroelectric (556 MW) and landfill gas (64 MW) made up less than 1% of winter capacity in December 2020. [29] Hydroelectric generation ramped up on Feb. 15 just before rotating outages were ordered (Figure 10). No failures have been reported at hydroelectric or landfill gas generators. However, as the capacity from these sources is minimal, they had only minor impacts.

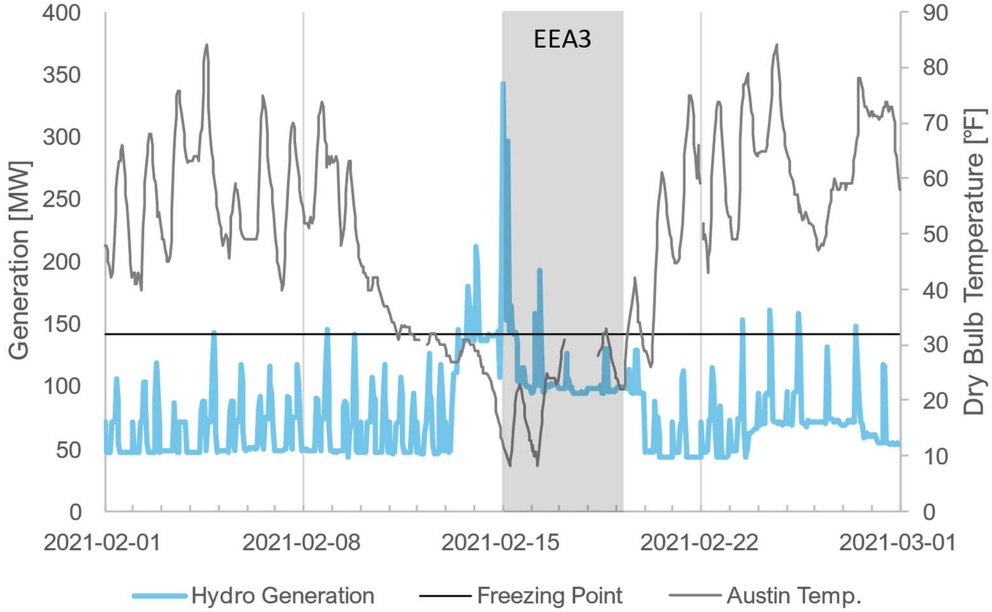

Figure 10. Hydroelectric generation [25] and dry bulb air temperatures at Fort Stockton and Midland [18], Feb. 2021. Energy Emergency Alert Level 3 (EEA3) is shown in the grey box, active Feb. 15 01:20 until Feb. 19 09:00 CST.

5 Other Grid Resources

5.1 CHP

Combined heat and power (CHP)[4] plants could contribute over 11 GW of capacity within ERCOT. [36] However, ERCOT assumed that less than 4 GW would be available during winter 2020–21. [9] These generators are mostly sited at refineries and chemical plants. Their primary purpose is industrial energy production, and they are self-dispatched.

It is unknown if ERCOT called on them to maximize grid generation during the supply emergency. Since these plants are fueled by pipeline natural gas, gas shortages also affected their availability. [37]

5.2 Emergency Import Capacity

ERCOT has limited interconnection capacity with other grids. Two DC ties connect with the Southwest Power Pool/SPP (about 800 MW), and a DC tie and variable frequency transformer connect with Mexico's Centro Nacional de Control de Energía/CENACE (about 400 MW). [9] These interconnections are primarily available for emergency situations. [38]

Imports from CENACE dropped to zero on Feb. 15, while those from SPP became intermittent for much of the week as these regions were also experiencing high demand due to the same weather event (Figure 11). The natural gas supply shortages in Texas caused generation losses and blackouts in northern Mexico. [39] The Southwest Power Pool resorted to load shedding on Feb. 15 and 16, the first time in its history. [40]

4 ERCOT refers to these CHP plants as private-use networks (PUN).

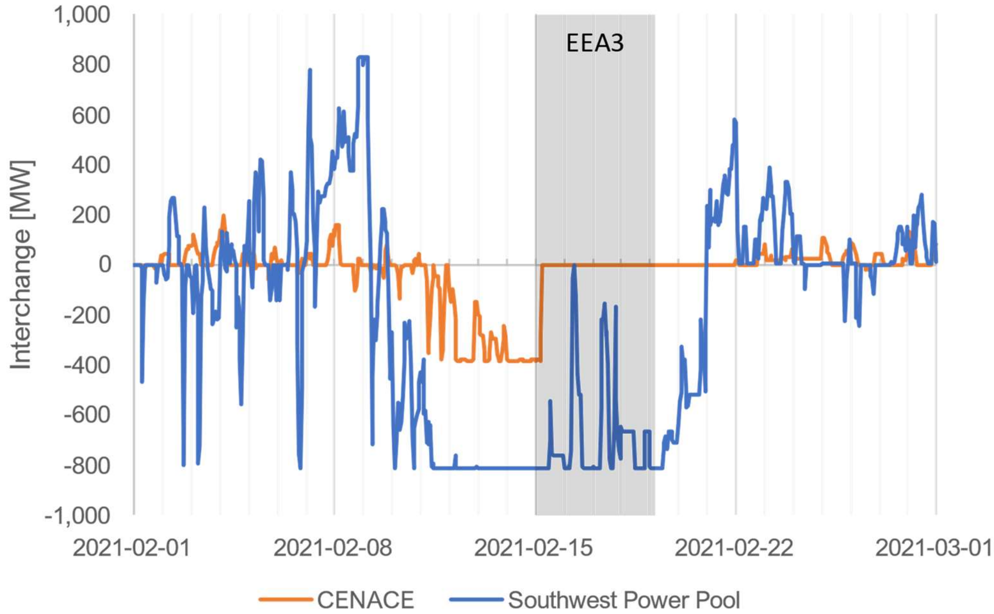

Figure 11. ERCOT hourly electricity interchange during the Feb. 2021 cold weather event. [25] Energy Emergency Alert Level 3 (EEA3) is shown in the grey box, active Feb. 15 01:20 until Feb. 19 09:00 CST.

5.3 Seasonal Mothballs

Over 600 MW of capacity was unavailable as seasonally mothballed until the beginning of the summer peaking season in May. This included two natural gas power plants (about 500 MW) and a biomass power plant (about 100 MW). [9]

5.4 Energy Storage

ERCOT has a growing number of battery energy storage systems, with most built since 2017. However, the total power capacity was only 180 MW for the 2020–21 season. [9] These battery systems are nearly all of short duration; through the end of 2019, battery systems with durations of one hour or less accounted for 90% of battery capacity (in MW). [41] Data is not universally available for 2020, but at least 61% of new battery capacity (in MW) installed during 2020 will also have a one hour or less duration. [9], [42]

5.5 Transmission and Distribution

Transmission and distribution equipment can be damaged by extreme cold temperatures. ERCOT does not publish outage data for transmission systems without consent from the equipment owners. It is still uncertain whether electric transmission infrastructure outages played a role in the extended blackouts. The North American Electric Reliability Corporation (NERC) collects outage information and publishes an annual State of Reliability Report with summaries for each reliability region. [43] However, 2021 information will not be published until 2022.

6 Generating Capacity Risks and Incentives

6.1 Seasonal Capacity Risks

ERCOT plans separately for summer and winter seasonal resource adequacy. It calculates the expected reserve capacity by applying derating factors to the different resource types. For example, wind generators in West Texas are only expected to operate at 19% of nameplate capacity for the reserves analysis.

ERCOT also analyzes a high-risk case that includes both extreme peak load and significant generator outages simultaneously. The extreme peak load case is based upon the experience in Feb. 2011 at 67 GW. [9] However, actual load exceeded 69 GW on Feb. 14 a few hours before the initial loss of generation and forced load outages (Figure 2). The unmet forecast load on Feb. 15 remained above 70 GW for nearly the entire day, but the rotating outages pushed actual load much lower. The peak forecast load on Feb. 15 and 16 exceeded 75 GW, comparable to the 2020 summer peak and the all-time summer peak load set in Aug. 2019 and well above the extreme winter peak load prediction. [27]

The high-risk case also included about 5 GW of additional forced outages due to fuel limitations, but this was based on a less-severe cold weather event in Jan. 2018. [9] The 30 GW of forced generation outages experienced in the Feb. 2011 cold weather event was not considered.

6.2 Capacity Incentives

ERCOT's posture towards ensuring adequate generation capacity is unique among all US markets. Other markets have instituted explicit forward capacity auctions, whereby generators are compensated for their guarantee to provide a certain amount of capacity to the grid in certain future years. ERCOT, by contrast, relies exclusively on a scarcity-pricing mechanism which provides lower electricity prices most of the time, but dramatically increases market electricity prices whenever reserves (total available capacity minus demand) are low. When scarcity pricing is high, generators should be incentivized to build additional capacity in order to permanently capture a portion of that revenue for themselves, thereby increasing system supply and lowering prices. The function which computes this scarcity price, in real time for every five-minute period of the year, is called the Operating Reserve Demand Curve (ORDC).

From an economic-theoretical point of view, a well-designed scarcity pricing mechanism should produce equivalent outcomes to the capacity auction, without the need for regulatory intervention in the market process. Given sufficient data, it should be possible to choose a function for setting the scarcity prices which results in the desired level of system reserves. ERCOT nominally targets a reserve margin during the summer peak of 13.75%. [44] However, it can be observed from market trends in ERCOT that the extant form of the ORDC was consistently insufficient to incentivize significant new investments in thermal generation.

In recent years, the frequency of extreme pricing events in ERCOT has been increasing. The ERCOT independent market monitor, Potomac Economics, has noted for several years that the total remuneration afforded by the ORDC has been well below levels needed to incentivize entry of new thermal generation into the system. [45] Between 2014 and 2017, system-wide prices (i.e., excluding locational marginal prices) exceeded $1,000/MWh for less than 4.5 hours per year. In 2018 and 2019, market prices exceeded $1,000/MWh for a total of 19 and 15 hours, respectively. [30] This is reflective of the decreasing reserve margin available in Texas during the summer months; compared to the nominal target of 13.75%, in 2019 the reserve reached its lowest-ever value of

8.6%. [44] This increase in scarcity pricing is a normal function of the pricing mechanism in response to reduced supply margins. However, no new thermal generation has been installed in ERCOT since 2018, despite this intended market signal. [46]

In January 2019, ERCOT approved a change to the ORDC calculation methodology which increased compensation during periods of scarcity. The goal of this change was to more effectively incentivize investments in new thermal and other generation capacity in Texas and improve reserve margins. The effect of this change was immediately apparent: of a total weighted average electricity price of $47.06 in ERCOT in 2019, Potomac Economics estimates that $6–7 of that amount was accounted for by increased ORDC price adders. [44] In fact, ERCOT data shows that nearly 2,000 MW of new natural gas capacity installations and power uprates are scheduled for 2021 and beyond. Except for 33 MW of this capacity, all of these projects were initiated after the ORDC change. However, none of these capacity additions were completed in time for the February 2021 outages. [46] Even if these planned generators had been available without fuel shortages, their total capacity would have made up only a fraction of the unserved demand during the cold weather event.

7 Social and Economic Impacts

Over four million customers in ERCOT went without power on Feb. 15 [47]. Power outages were reduced as the week went on, with ERCOT ending emergency operations on Feb. 19. [24]

Several deaths and injuries occurred due to hypothermia and carbon monoxide poisoning, and there will likely be additional deaths attributed to the power failures. The lack of electricity caused water shortages and treatment outages, putting nearly half of Texas' population under boil water notices. [48] Many homes and businesses also had water pipes freeze and burst, causing additional wide-spread property damage. [49]

Wholesale electricity prices which normally range from $20–40/MWh began steadily rising on Feb. 12, and they reached the maximum price of $9,000/MWh just before emergency load shedding began on Feb. 15. Prices stayed at or near the system-wide offer cap ($9,000/MWh) for about 90 hours (Figure 12). [3] Compare this to 2019, when summer peak prices reached $9,000/MWh for 30 minutes. [30]

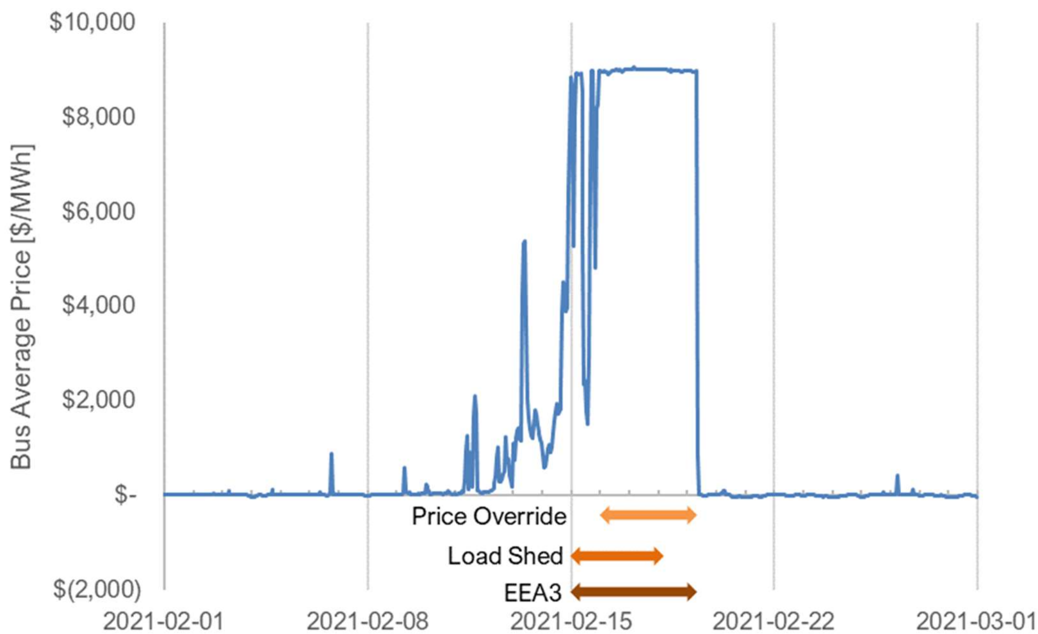

Figure 12. ERCOT bus-average price for Feb. 2021. [3] A PUC-mandated Price Override occurred Feb. 16 00:00 until Feb. 19 09:00 CST. ERCOT implemented firm load shed Feb. 15 01:20 until Feb. 17 23:55 CST. ERCOT operated at Energy Emergency Alert Level 3 (EEA3) Feb. 15 01:20 until Feb. 19 09:00 CST.

Prices were set manually for most of the emergency, but this caused later conflicts over prices after load shedding stopped but before the emergency status was lifted. On Feb. 15, ERCOT alerted the Public Utility Commission of Texas (PUCT) that market prices were clearing well below the maximum despite forced load shedding. PUCT responded by ordering ERCOT to include unserved load in its scarcity price calculations, effectively forcing prices to the maximum. [50] ERCOT ended firm load shedding just before midnight Feb. 17, but prices remained fixed at the maximum until the emergency alert was ended on Feb. 19 at 09:00 CST. [51]

ERCOT's market monitor, Potomac Economics, argued to the PUCT that pricing should have returned to normal market calculations when firm load shedding ended the night of Feb. 17. [52] This suggested that 33 hours should be repriced. Given that the average load on Feb. 18 was about 50 GW, around $15 billion in charges would be reduced. However, most demand was actually served by bilateral contracts or self-generation, so a revised estimate put the reduction closer to $3 billion. [53]

Some retail customers saw daily charges of several hundred dollars during the crisis. [54] The retail electric provider Griddy was forced to shut down after it failed to make payments on behalf of its customers, who were paying wholesale market prices. [55] The largest electric cooperative in Texas, Brazos Electric, filed for bankruptcy protection after it was unable to pay nearly $2 billion in charges for the week. [56], [57] On the other extreme, it was reported that Macquarie Group, an energy trading firm, earned over $200 million during the emergency. [58]

The natural gas production shortages drove physical delivery prices to record highs: the Katy hub crested $350/MMBtu, while the Houston Ship Channel hub reached $400/MMbtu. Prior week prices were around $4/MMBtu. [4]

8 Related Historical Events

Although the cold weather event was notable for its extremely cold temperatures, duration, and geographic scope, it was not unprecedented. Texas experienced very similar events in 1989 and 2011, and the Great Lakes and northeastern United States dealt with an unstable polar vortex in 2014.

Frozen instrumentation was the cause of most generator malfunctions in the Dec. 1989 cold weather event. Valves, pumps, and water lines also failed due to the very low temperatures. [12] Common recommendations included the installation and maintenance of heat trace, insulation, and wind breaks.

These system failures continued to plague Texas generators in the Feb. 2011 cold weather event. [14] Like 2021, extremely low temperatures and wind chills over several days caused natural gas production shortages, generator outages, and load shedding to prevent a complete blackout. [11] Most of the problems during that event stemmed from cold weather-induced generator outages, especially from frozen equipment like instrumentation and valves. Additional problems came from natural gas supply shortages. These were caused by pipeline freeze-offs, frozen equipment, treacherous roads preventing timely repairs, and electric blackouts. [11]

The large installed wind capacity in 2021 made ERCOT grid planning and operations significantly different than in 2011 or 1989. Wind turbines use a variety of mechanisms that are susceptible to freezing weather without engineered mitigations. Turbine blades are subject to icing (like airplane wings), and turbine nacelles can fault in cold weather due to gearbox oil or radiator failures. [31]

The early Jan. 2014 cold weather event led to new winter peak load records in ERCOT, MISO, PJM, SPP, and much of the southeastern U.S. [10] Natural gas production problems were again a major factor, as was frozen generation equipment in the southeast where generators had not been designed to operate in extended sub-freezing weather. More non-weather-related outages were reported, even on the coldest night. Unlike the three major events in Texas, very little load was shed in the affected regions.

9 Preliminary Analysis and Risk Mitigation Suggestions

9.1 Seasonal Planning Should Include More Extreme Weather and Generation Losses

Planning for extreme cold weather events should be revised. The assumed extremes for load and generation outages were far less severe than the actual extremes of Feb. 2021. The major, sustained outages were a type of beyond design basis accident. [59]

For ERCOT, the planning focus has typically been on record summer peak loads, but summer heat tends to build slowly over time. Winter cold fronts can be sudden and extreme, and given the magnitude of load swings, they should be given greater attention in capacity and availability planning. [28]

For example, ERCOT's Seasonal Assessment of System Adequacy (SARA) assumed an extreme winter peak load of about 67 GW based on the 2011 system experience. The probable Feb. 2021 peak load, if it were met, would have been around 75 GW. Likewise, the extreme forced outage case assumed about 14 GW of thermal capacity would be unavailable. This amount of thermal capacity was already offline on Feb. 14 before the major supply disruptions began. Feb. 15–17 saw over 30 GW of thermal capacity offline. [5] Wind outages were also significant, causing wind generation to underperform relative to expectations.

Given the risks of unexpected extreme winter storms, it would be prudent to allow fewer maintenance and refueling outages in the region during the winter season Dec.–Feb. Although forced outages were a direct cause of the Feb. 2021 blackouts, outages in the week leading up to the event were significant and might have been a contributing factor. [5] Excess outages leading up to generation shortages played a role in the Jan. 2014 cold weather event as well.

Nuclear refueling outages should be given special consideration given their multi-year lead times and multi-week durations. Since 2016, December, January, July, and August have had the lowest nuclear capacity outages. [60] In other words, they have been typically scheduled in the spring and fall when demand is lowest.

9.2 Power Plant Engineering Design Bases for Extreme Weather Events Should Be Reevaluated

Plant design temperature ranges might be too narrow for infrequent extreme cold or hot weather events. This was specifically analyzed by the Texas Public Utility Commission in 1990. [12] This situation contributed to at least one major power plant outage in 2011. [13] The more rapid heat loss rate from wind chill should also be accounted for. [13] If climate change and global heating continue unabated, power plants will likely encounter more extreme weather events outside their original engineering design.

Both units at STP have steam turbines partially exposed to the environment. Some Combustion Engineering and Westinghouse designs were built with exposed systems at several plants, mostly in the South and Southeast U.S. (Comanche Peak, St. Lucie, Turkey Point). Salem in New Jersey is the only plant of this type in a colder region.

The North American Electric Reliability Corporation maintains a reliability guideline for generator cold weather readiness [61]. This report identifies commonly-affected critical components at power plants (including pressure transmitters, sensing lines, and valves, among others) and links to further reports on specific historical events.

9.3 Revisit Price Incentives for Capacity Availability

Considering that the total theoretical shortfall was likely around 30 GW, a very large quantity of additional capacity would have been required in order to mitigate the February 2021 outages in the absence of other measures. However, as part of a broader systemic review to prevent similar events in the future, increasing system capacity would provide a more robust margin to protect against systemic forced outages. An explicit forward capacity market would be one method for ensuring available capacity for future winter periods. In the short term, it is not likely to be politically feasible to implement such a radically different system given the entrenched preference for market-based solutions; in that case, further expanding the compensation provided through the ERCOT scarcity mechanisms is the most immediately available solution.

However, it is likely that the costs of further winterizing existing power plants would be lower than building new power plants, but these might be borne by different market participants. Performance and unavailability penalties would increase the expected cost of extreme weather events to utilities, and would therefore likely spur additional adoption of robust winterization measures. In ERCOT, if a generator offers energy on the market and their offer is accepted, the penalty assessed for failing to generate that energy is equivalent to the cost of acquiring the same amount of energy on the spot market: the price during the period in question, multiplied by the amount of energy not provided. The ERCOT Nodal Operating Guides specify that during a declared emergency, generators may not remove on-line generation resources from service unless failure to do so would violate safety or regulatory requirements. [62, Sec. 4.5.3.2(1)(i)] The primary economic motivator is potential loss of revenue during scarcity events.

Furthermore, it is apparent from past experience that the existing economic incentives and regulations in ERCOT are insufficient to cause universal, robust winterization of generation assets.

Previous extreme-cold events in 1989 and 2011 also caused substantial power outages and harm to Texas residents, but a large proportion of the Texas grid was not sufficiently winterized to weather Winter Storm Uri. Either some new market mechanism to incentivize such behavior must be developed, or regulation backed by motivating penalties must be implemented in order to produce meaningful updates to infrastructure.

9.4 Fuel Supplies Should be Secured and Tested Ahead of Multi-Day Extreme Weather Events

Natural gas supply shortages for electric generators could be addressed in three major ways: mitigating production susceptibility, increasing bulk natural gas storage, and on-site fuel storage. Natural gas wells and processing facilities could be retrofitted to operate in colder conditions, reducing the risk of freeze-offs and production declines. Increasing bulk storage capacity would be akin to the Strategic Petroleum Reserve, but with the goal of seasonal reliability. Finally, on-site natural gas or backup fuel could be stored on-site at generators as an emergency supply. On-site natural gas storage would require the construction of large tanks, which would be much more expensive than bulk storage in underground reservoirs. Some gas turbines were designed to run on fuel oil as a backup fuel, but it is unclear if other turbines could be economically retrofitted for dual-fuel operation. However, fuel oil delivery could also be impacted by severe cold weather. [10], [63]

Other thermal power plants, including biomass, coal, and nuclear, are not subject to the types of fuel delivery risks as natural gas power plants. The storage of large quantities of coal and biomass at plant sites generally mitigates short-term fuel delivery risks. Nuclear refueling outages are generally done in spring and fall seasons.

9.5 Natural Gas Planning Should Be Better Coordinated with Electricity Planning

Natural gas has a unique role in serving heating and electricity demand. Natural gas production, compression, and instrumentation are typically electrically-powered, and even brief power outages can cause gas production and transmission to fail. [64] Because of their interconnectedness, a power blackout can create a cascading failure if gas supplies to gas-fired generators are cut.

Extreme weather planning should be tightly coordinated between the natural gas and electricity sectors because of the shared risks. If all natural gas-fired generators lowered their cold weather outage risk with winterization upgrades, they would still be susceptible to natural gas supply shortages if natural gas production and processing facilities were not similarly upgraded.

GLOSSARY

Acronyms and Abbreviations

CENACE	Centro Nacional de Control de Energía
CHP	Combined heat and power
CST	Central Standard Time
DC	Direct current
EEA	Energy emergency alert
ERCOT	Electric Reliability Council of Texas
MISO	Midcontinent Independent System Operator
NERC	North American Electric Reliability Corporation
ORDC	Operating reserve demand curve
PUCT	Public Utility Commission of Texas
PUN	Private use network
PV	Photovoltaic
SARA	Seasonal Assessment of Resource Adequacy
SPP	Southwest Power Pool
STP	South Texas Project
TDSP	Transmission and distribution service provider

Units

Bcf	Billion standard cubic feet
GW	Gigawatt, one billion watts
MMBtu	Million British thermal units
MW	Megawatt, one million watts

References

[1] U.S. Census Bureau, “House Heating Fuel, 2019 American Community Survey 1-Year Estimates Data Profiles,” Feb. 02, 2021. https://data.census.gov/cedsci/table?g=0400000US48&tid=ACSDP1Y2019.DP04 (accessed Feb. 26, 2021).

[2] Electric Reliability Council of Texas, “ERCOT Fact Sheet 2021.” Feb. 25, 2021. Accessed: Feb. 26, 2021. [Online]. Available: http://www.ercot.com/content/wcm/lists/219736/ERCOT_Fact_Sheet_2.25.21.pdf

[3] Electric Reliability Council of Texas, “Historical RTM Load Zone and Hub Prices,” Mar. 2021. Accessed: Mar. 12, 2021. [Online]. Available: http://www.ercot.com/mktinfo/prices

[4] U.S. Energy Information Administration (EIA), “Natural Gas Weekly Update for Week Ending February 24, 2021,” Feb. 25, 2021. https://www.eia.gov/naturalgas/weekly/archivenew_ngwu/2021/02_25/ (accessed Feb. 26, 2021).

[5] B. Magness, “Review of February 2021 Extreme Cold Weather Event – ERCOT Presentation,” Feb. 24, 2021. [Online]. Available: http://www.ercot.com/content/wcm/key_documents_lists/225373/Urgent_Board_of_Directors_Meeting_2-24-2021.pdf

[6] U.S. Nuclear Regulatory Commission, “Event Notification Report For February 17, 2021,” *NRC Web*, Feb. 17, 2021. https://www.nrc.gov/reading-rm/doc-collections/event-status/event/2021/20210217en.html (accessed Feb. 26, 2021).

[7] STP Nuclear Operating Company, “South Texas Project Unit 1 Returns to ERCOT Grid,” *Recent News*, Feb. 18, 2021. http://www.stpnoc.com (accessed Feb. 26, 2021).

[8] R. Adams, “South Texas Project Unit 1 tripped at 0537 on Feb 15, 2021,” *Atomic Insights*, Feb. 15, 2021. https://atomicinsights.com/south-texas-project-unit-1-tripped-at-0537-on-feb-15-2021/ (accessed Mar. 19, 2021).

[9] Electric Reliability Council of Texas, “Seasonal Assessment of Resource Adequacy for the ERCOT Region (SARA) Winter 2020/2021,” Electric Reliability Council of Texas, Nov. 2020. Accessed: Feb. 25, 2021. [Online]. Available: http://www.ercot.com/content/wcm/lists/197378/SARA-FinalWinter2020-2021.pdf

[10] North American Electric Reliability Corporation, “Polar Vortex Review,” Sep. 2014. Accessed: Feb. 26, 2021. [Online]. Available: https://www.nerc.com/pa/rrm/January%202014%20Polar%20Vortex%20Review/Polar_Vortex_Review_29_Sept_2014_Final.pdf

[11] Federal Energy Regulatory Commission and North American Electric Reliability Corporation, “Report on Outages and Curtailments During the Southwest Cold Weather Event of February 1-5, 2011,” Aug. 2011. Accessed: Feb. 25, 2021. [Online]. Available: https://www.ferc.gov/sites/default/files/2020-05/ReportontheSouthwestColdWeatherEventfromFebruary2011Report.pdf

[12] Public Utility Commission of Texas, “Electric Utility Response to the Winter Freeze of December 21 to December 23, 1989,” Nov. 1990. https://lrl.texas.gov/scanned/archive/1990/15303.pdf (accessed Feb. 25, 2021).

[13] North American Electric Reliability Corporation, “Lesson Learned – Generating Unit Temperature Design Parameters and Extreme Winter Conditions,” North American Electric Reliability Corporation, Sep. 2011. Accessed: Feb. 25, 2021. [Online]. Available: https://www.nerc.com/pa/rrm/ea/Lessons%20Learned%20Document%20Library/LL20110903_Generating_Unit_Temperature_Design_Parameters_and_Extreme_Winter_Conditions.pdf

[14] North American Electric Reliability Corporation, “Lesson Learned – Plant Instrument Transmitters and Sensing Equipment Freezing due to Heat Trace and Insulation Failures,” North American Electric Reliability Corporation, Oct. 2011. Accessed: Feb. 25, 2021. [Online]. Available: https://www.nerc.com/pa/rrm/ea/Lessons%20Learned%20Document%20Library/LL20111001_Plant_Instrument_and_Sending_Equipment_Freezing_Due_to_Heat_Trace_and_Insulation_Failures.pdf

[15] NOAA National Weather Service, “Daily Weather Maps.” https://www.wpc.ncep.noaa.gov/dailywxmap/ (accessed Mar. 17, 2021).

[16] NOAA National Weather Service, “Valentine’s Week Winter Outbreak 2021: Snow, Ice, & Record Cold,” *NWS Forecast Office Houston/Galveston, TX*. https://www.weather.gov/hgx/2021ValentineStorm (accessed Mar. 17, 2021).

[17] NOAA Climate.gov, “Climate Variability: Arctic Oscillation,” Aug. 30, 2009. https://www.climate.gov/news-features/understanding-climate/climate-variability-arctic-oscillation (accessed Mar. 17, 2021).

[18] D. Herzmann, “Download ASOS/AWOS/METAR Data,” *Iowa Environmental Mesonet*, Mar. 02, 2021. https://mesonet.agron.iastate.edu/request/download.phtml?network=TX_ASOS (accessed Mar. 02, 2021).

[19] The Weather Channel, “Coldest Outbreak in Over 30 Years Smashes Records in Southern Plains; Some Relief By Next Week,” *The Weather Channel*, Feb. 16, 2021. https://weather.com/safety/winter/news/2021-02-14-record-cold-temperatures-plains-midwest-february (accessed Feb. 24, 2021).

[20] NOAA National Centers for Environmental Information, “Weekly Divisional Products | Temperature, Precipitation, and Drought.” https://www.ncdc.noaa.gov/temp-and-precip/us-weekly/ (accessed Feb. 24, 2021).

[21] Electric Reliability Council of Texas, “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 Feb. 25, 2021).

[22] E. Douglas, “Texas was ‘seconds and minutes’ away from catastrophic monthslong blackouts, officials say,” *The Texas Tribune*, Feb. 18, 2021. https://www.texastribune.org/2021/02/18/texas-power-outages-ercot/ (accessed Mar. 06, 2021).

[23] Electric Reliability Council of Texas, “Grid operator restores more power overnight,” Feb. 17, 2021. http://www.ercot.com/news/releases/show/225369 (accessed Mar. 06, 2021).

[24] Electric Reliability Council of Texas, “ERCOT will end emergency conditions today,” Feb. 19, 2021. http://www.ercot.com/news/releases/show/225962 (accessed Feb. 25, 2021).

[25] U.S. Energy Information Administration (EIA), "Hourly Electric Grid Monitor." https://www.eia.gov/beta/electricity/gridmonitor/dashboard/custom/pending (accessed Feb. 25, 2021).

[26] WFAA, "'We have seen nothing like this': ERCOT CEO says agency still can't predict when Texas power outages will end during Q&A," *wfaa.com*, Feb. 18, 2021. https://www.wfaa.com/article/news/local/we-have-seen-nothing-like-this-ercot-ceo-says-agency-still-cant-predict-when-texas-power-outages-will-end/287-6fb9564b-fd08-4ec6-acf5-a022971720ad (accessed Feb. 25, 2021).

[27] Electric Reliability Council of Texas, "ERCOT reserve margin up for summer 2020, energy alerts still possible," May 13, 2020. http://www.ercot.com/news/releases/show/206275 (accessed Feb. 25, 2021).

[28] C. Coleman, "2020-21 Preliminary Winter Weather Outlook," presented at the ERCOT and Texas RE Generator Winter Weatherization Workshop, Sep. 03, 2020. Accessed: Feb. 25, 2021. [Online]. Available: http://www.ercot.com/content/wcm/key_documents_lists/210163/8._Weatherization_workshop_winter_weather_forecast_2020_2021_final.pdf

[29] Electric Reliability Council of Texas, "Capacity, Demand and Reserves Report December 2020," Electric Reliability Council of Texas, Dec. 2020. Accessed: Mar. 02, 2021. [Online]. Available: http://www.ercot.com/content/wcm/lists/197379/CapacityDemandandReservesReport_Dec2020.xlsx

[30] Electric Reliability Council of Texas, "Historical Real-Time ORDC and Reliability Deployment Price Adders and Reserves," Electric Reliability Council of Texas, Feb. 2021. Accessed: Mar. 04, 2021. [Online]. Available: http://mis.ercot.com/misapp/GetReports.do?reportTypeId=13231&reportTitle=Historical%20Real-Time%20ORDC%20and%20Reliability%20Deployment%20Price%20Adders%20and%20Reserves&showHTMLView=&mimicKey

[31] North American Electric Reliability Corporation, "Lesson Learned – Wind Farm Winter Storm Issues," North American Electric Reliability Corporation, Sep. 2012. Accessed: Feb. 25, 2021. [Online]. Available: https://www.nerc.com/pa/rrm/ea/Lessons%20Learned%20Document%20Library/LL20120901_Wind_Farm_Winter_Storm_Issues.pdf

[32] G. Meyer, "Power producer Vistra faces $1bn hit from Texas freeze," *Financial Times*, Feb. 26, 2021. https://www.ft.com/content/6a249066-0b0e-4da1-8310-e1c910ce0bc3 (accessed Mar. 19, 2021).

[33] U.S. Nuclear Regulatory Commission, "Power Reactor Status Reports For 2021," *NRC Web*, Feb. 26, 2021. https://www.nrc.gov/reading-rm/doc-collections/event-status/reactor-status/2021/index.html (accessed Feb. 26, 2021).

[34] R. Adams, "Preliminary lessons available to be learned from Feb 2021 extended cold spell," *Atomic Insights*, Feb. 22, 2021. https://atomicinsights.com/preliminary-lessons-available-to-be-learned-from-feb-2021-extended-cold-spell/ (accessed Mar. 15, 2021).

[35] Entergy Nuclear, “River Bend Station #nuclear power plant in Louisiana has commenced its 21st scheduled refueling and maintenance outage. https://t.co/LnLIsJV4e6,” *@EntergyNuclear*, Feb. 21, 2021. https://twitter.com/EntergyNuclear/status/1363561510061166593 (accessed Feb. 26, 2021).

[36] U.S. Environmental Protection Agency, “eGRID: Download Data,” *US EPA*, Aug. 20, 2020. https://www.epa.gov/egrid/download-data (accessed Mar. 11, 2021).

[37] U.S. Energy Information Administration (EIA), “This Week In Petroleum,” Feb. 24, 2021. https://www.eia.gov/petroleum/weekly/archive/2021/210224/includes/analysis_print.php (accessed Mar. 11, 2021).

[38] Electric Reliability Council of Texas and Southwest Power Pool, “Coordination Plan.” 2019. Accessed: Feb. 25, 2021. [Online]. Available: http://www.ercot.com/content/wcm/key_documents_lists/90055/ERCOT-SPP_Coordination_Plan__FINAL_.pdf

[39] S&P Global Platts, “Natural gas shortage in Texas causes blackout in Northern Mexico,” Feb. 15, 2021. https://www.spglobal.com/platts/en/market-insights/latest-news/natural-gas/021521-natural-gas-shortage-in-texas-causes-blackout-in-northern-mexico (accessed Feb. 25, 2021).

[40] B. Sugg, “A statement from Barbara Sugg, Southwest Power Pool president and chief executive officer,” *Southwest Power Pool*, Feb. 24, 2021. https://spp.org/newsroom/press-releases/a-statement-from-barbara-sugg-southwest-power-pool-president-and-chief-executive-officer/ (accessed Mar. 02, 2021).

[41] U.S. Energy Information Administration (EIA), “Form EIA-860 detailed data with previous form data (EIA-860A/860B),” *Electricity*, Sep. 15, 2020. https://www.eia.gov/electricity/data/eia860/ (accessed Mar. 04, 2021).

[42] A. Colthorpe, “‘Largest standalone battery project’ in Texas’ ERCOT market begins construction,” *Energy Storage News*, Aug. 25, 2020. https://www.energy-storage.news/news/largest-standalone-battery-project-in-texas-ercot-market-set-to-begin-const (accessed Mar. 04, 2021).

[43] North American Electric Reliability Corporation, “Performance Analysis,” 2021. https://www.nerc.com/pa/RAPA/PA/Pages/default.aspx (accessed Mar. 01, 2021).

[44] Potomac Economics, “2019 State of the Market Report for the ERCOT Electricity Markets,” May 2020. Accessed: Mar. 04, 2021. [Online]. Available: https://www.potomaceconomics.com/wp-content/uploads/2020/06/2019-State-of-the-Market-Report.pdf

[45] Potomac Economics, “2018 State of the Market Report for the ERCOT Electricity Markets,” Jun. 2019. [Online]. Available: https://www.potomaceconomics.com/wp-content/uploads/2019/06/2018-State-of-the-Market-Report.pdf

[46] Electric Reliability Council of Texas, “Capacity Changes by Fuel Type Charts, January 2021,” Electric Reliability Council of Texas, Feb. 2021. Accessed: Mar. 04, 2021. [Online]. Available: http://www.ercot.com/content/wcm/lists/219848/Capacity_Changes_by_Fuel_Type_Charts_January_2021.xlsx

[47] The Weather Channel, “Why Winter Storm Uri Caused Millions of Power Outages in Texas,” *The Weather Channel*, Feb. 16, 2021. https://weather.com/news/news/2021-02-16-why-so-many-power-outages-in-texas-winter-storm (accessed Feb. 25, 2021).

[48] The Weather Channel, “Dozens of Deaths Connected to Winter Storms This Week; 14 Million Texans Without Clean Drinking Water,” *The Weather Channel*, Feb. 26, 2021. https://weather.com/news/news/2021-02-19-winter-storm-texas-south-water-outages-snow-ice-cold (accessed Feb. 25, 2021).

[49] A. Waller and M. Felix, “What a Texas Plumber Faces Now: A State Full of Burst Pipes,” *The New York Times*, Feb. 21, 2021. Accessed: Mar. 18, 2021. [Online]. Available: https://www.nytimes.com/2021/02/21/us/texas-plumber-frozen-pipes.html

[50] Public Utility Commission of Texas, “Item 3, ORDER DIRECTING ERCOT TO TAKE ACTION AND GRANTING EXCEPTION,” Public Utility Commission of Texas, 51617, Feb. 2021. Accessed: Mar. 12, 2021. [Online]. Available: https://interchange.puc.texas.gov/Documents/51617_3_1111656.PDF

[51] B. Magness, “Texas Senate Jurisprudence Committee,” presented at the Texas Senate, Jurisprudence Committee, Austin, TX, Mar. 11, 2021. Accessed: Mar. 12, 2021. [Online]. Available: http://www.ercot.com/content/wcm/lists/226521/Senate_Jurisprudence_031021_FINAL.pdf

[52] Potomac Economics, “Item 61, Second Letter to Commissioners,” Public Utility Commission of Texas, 51812, Mar. 2021. Accessed: Mar. 12, 2021. [Online]. Available: https://interchange.puc.texas.gov/Documents/51812_61_1114183.PDF

[53] Potomac Economics, “Item 149, Follow Up Letter,” Public Utility Commission of Texas, 51812, Mar. 2021. Accessed: Mar. 12, 2021. [Online]. Available: https://interchange.puc.texas.gov/Documents/51812_149_1115720.PDF

[54] The Weather Channel, “Utility Bills Skyrocket Amid Recent Winter Storms,” *The Weather Channel*, Feb. 22, 2021. https://weather.com/news/news/2021-02-19-utility-bills-increase-winter-storms-texas (accessed Mar. 07, 2021).

[55] R. Carballo, “ERCOT shuts down Griddy, as Paxton sues Texas power retailer,” *Houston Chronicle*, Mar. 01, 2021. Accessed: Mar. 12, 2021. [Online]. Available: https://www.houstonchronicle.com/business/energy/article/AG-Ken-Paxton-sues-Griddy-alleging-deceptive-15988077.php

[56] Brazos Electric Power Cooperative, “Brazos Electric Power Cooperative, Inc. Files for Chapter 11 Financial Restructuring,” Mar. 01, 2021. http://www.brazoselectric.com/pressrelease.pdf (accessed Mar. 04, 2021).

[57] G. McWilliams, “Texas power cooperative files for bankruptcy, citing $1.8 billion grid debt,” *Reuters*, Mar. 02, 2021. https://www.reuters.com/article/us-bankruptcy-brazoselectric-texas-outag-idUSKCN2AT1FE (accessed Mar. 04, 2021).

[58] J. Wallace and R. Dezember, “Texas Blackout Boosts Australian Bank by Up to $215 Million,” *Wall Street Journal*, Feb. 22, 2021. Accessed: Mar. 04, 2021. [Online]. Available:

https://www.wsj.com/articles/texas-blackout-boosts-australian-bank-by-up-to-215-million-11613997617

[59] WFAA, “Texas power outages: How the largest energy-producing state in the US failed in freezing temperatures,” *wfaa.com*, Feb. 15, 2021. https://www.wfaa.com/article/news/local/texas/dallas-texas-electrical-power-outage-ercot-failures/287-50797307-0afe-43eb-8175-b78e7e4fc13a (accessed Feb. 25, 2021).

[60] U.S. Energy Information Administration (EIA), “Status of U.S. Nuclear Outages,” Mar. 03, 2021. https://www.eia.gov/nuclear/outages/ (accessed Mar. 03, 2021).

[61] North American Electric Reliability Corporation, “Reliability Guideline: Generating Unit Winter Weather Readiness – Current Industry Practices – Version 3,” North American Electric Reliability Corporation, Jun. 2020. Accessed: Feb. 25, 2021. [Online]. Available: https://www.nerc.com/comm/OC_Reliability_Guidelines_DL/Reliability_Guideline_Generating_Unit_Winter_Weather_Readiness_v3_Final.pdf

[62] Electric Reliability Council of Texas, “Section 4: Emergency Operation,” in *Nodal Operating Guides*, 2021. Accessed: Mar. 11, 2021. [Online]. Available: http://www.ercot.com/mktrules/guides/noperating/current

[63] North American Electric Reliability Corporation, “Lesson Learned – Plant Fuel Switching and Cold Weather,” North American Electric Reliability Corporation, Oct. 2011. Accessed: Mar. 02, 2021. [Online]. Available: https://www.nerc.com/pa/rrm/ea/Lessons%20Learned%20Document%20Library/LL20111002_Plant_Fuel_Switching_and_Cold_Weather.pdf

[64] North American Electric Reliability Corporation, “Lesson Learned – Electricity and Natural Gas Interdependency,” North American Electric Reliability Corporation, Sep. 2012. Accessed: Feb. 25, 2021. [Online]. Available: https://www.nerc.com/pa/rrm/ea/Lessons%20Learned%20Document%20Library/LL20120905_Gas_and_Electricity_Interdependency.pdf

Nuclear Science and Engineering Division
Argonne National Laboratory
9700 South Cass Avenue, Bldg. 205
Argonne, IL 60439

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