Electric Power Systems Research 217 (2023) 109124

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

The February 2021 U.S. Southwest power crisis

Srijana Shrestha *, Vinushika Panchalogaranjan, Paul Moses

School of Electrical and Computer Engineering, University of Oklahoma, Norman, OK, United States of America

ARTICLE INFO

Keywords:
Texas power crisis
Stability
Snow storm

ABSTRACT

A major blackout occurred in the U.S. Texas during a week of unseasonably cold weather starting from February 13, 2021. Despite advanced knowledge of the extreme weather, there was limited mitigation available to minimize the extent of disruptions. The events resulted in a forced reduction of consumption (e.g., rolling blackouts and equipment failures) during a time when electrical energy was already in high demand due to the cold weather. When primary generation systems started to fail from freezing conditions (48.6% loss of normal generation at its peak), the utility operators were forced to progressively issue rolling blackouts to maintain system frequency and avoid a complete blackout. While Texas avoided a complete grid collapse, 4.5 million customer premises were blacked out with economic losses estimated to be at least $130 billion and many lives lost. The cold weather affected the neighboring state of Oklahoma, however, the disruptions to electricity were mild when compared with Texas. This paper documents some of the key contributing factors in this event for the U.S. Southwest region based on factual data available to date. Wider electric energy reliability issues beyond the affected area are also highlighted.

1. Introduction

Severe weather events impacting power grids are mostly a known and anticipated occurrence in many regions. Transmission and distribution system operators are accustomed to preparing for a variety of contingencies by continually playing the ''what-if'' game for many failure scenarios. For events causing single-point failures such as a downed transmission line or a faulty major component, power can often be rerouted along alternative pathways to distribution substations with the backbone bulk power transmission system. However, as witnessed over the past year, there have been notable disruptions that have exceeded traditional contingency planning. Such is the case of the February 2021 winter storm Uri that led to cascading power system failures in Texas and Oklahoma. Although the winter storm Uri 2021 affected Oklahoma and Texas with extreme cold weather conditions, consumers in Texas experienced a more severe impact on their electricity and natural gas infrastructures than the Oklahoma power infrastructure. This analysis sheds some light on the salient factors that led to vastly different impacts in these regions.

The winter storm in 2021 was a rare event whose impacts significantly exceeded prior disruptions. The devastating impacts extended beyond just the electric grid affecting natural gas plants, and water supply systems. A similar, but less severe, event happened in 2011 February, and in 1989 December leading to failing power system infrastructure. All three events are found to have a common cause that led to the failure of infrastructure. Increased demand for electricity, frozen equipment, loss in natural gas supply, and so on were the common causes behind the loss of generating equipment. Outage reports from the events of 1989 and 2011 have both highlighted the inter-dependency of natural gas and electrical infrastructure and yet it again became one of the significant causes of generating equipment failure [1]. However, the latest event had the most severe consequence leading to power outages exceeding 20,000 MW at their worst point. It led to a shortage of food, water, and heat, and left millions of homes without electricity killing more than a hundred people [2].

Lately, the frequency of such extreme weather events including hurricanes, floods, and winter storms has been increasing in the U.S. Fig. 1 shows the number of billion-dollar disasters in the U.S. The average number of such events has increased exponentially in the last decade [3]. The report ''Our Changing Climate'' published by the U.S. Global Change Research Program reports that the frequency of such extreme weather events that lead to billion-dollar disasters is increasing with climate change [4].

Extreme weather has led to large blackouts and the destruction of power grids that takes weeks and months to restore. In 2021 alone, the U.S. faced other major weather events such as Hurricane Ida which made landfall in Louisiana and knocked out 8 high voltage transmission lines leaving at least 1.2 million customers without power [5,6].

* Corresponding author.
E-mail addresses: srijanashrestha@ou.edu (S. Shrestha), pmoses@ou.edu (P. Moses).
URL: https://leeps.oucreate.com/ (P. Moses).

https://doi.org/10.1016/j.epsr.2023.109124
Received 29 June 2022; Received in revised form 5 January 2023; Accepted 6 January 2023
Available online 12 January 2023

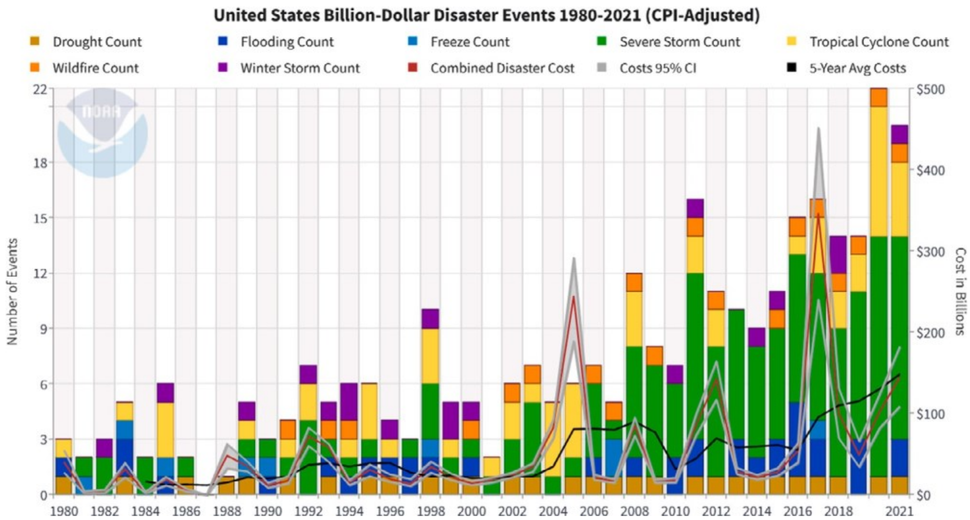

Fig. 1. Number of disaster events in the United State from 1980 to 2020.

In power systems, the generation and transmission system is the most critical infrastructure to oversee reliability. However, there are instances where the downstream distribution system can be heavily impacted as was seen a few months earlier in October 2020 in the State of Oklahoma, despite the transmission system not experiencing failures like the Texas grid.

2. The structure of the U.S. power grid and system operations relating to the failure

The North American electrical infrastructure consists of 2 major (Western and Eastern) and 3 minor (Quebec, Texas, and Alaska) alternating current (ac) grids, also known as interconnections (Fig. 2) [7]. Each interconnection operates at a synchronized frequency of 60 Hz ac, partially decoupled from other 60 Hz interconnections via High Voltage Direct Current (HVDC) transmission ties. Within each interconnection, there are power pool operators that fall into two categories:

Regional Transmission Operators (RTOs) and Independent System Operators (ISOs). Both coordinate with utilities to jointly operate and schedule generation in a cost-effective manner, and issue critical directives to utilities during emergencies. These entities are answerable to the North American Electric Reliability Corporation (NERC) for meeting reliability standards. The Electric Reliability Council of Texas (ERCOT) [8] is the ISO that issues the key directives to electric utilities in Texas. Similarly, Southwest Power Pool (SPP) manages the electric grid and wholesale electricity market in Oklahoma and 13 other states [9]. RTOs/ISOs routinely perform real-time simulations of many single-point failures on the transmission network under various loading and generation conditions. The goal is to manage grid resources to maintain normal operation for customers even after suffering a loss of one critical component such as a downed transmission line or generator. This is known as the N-1 criterion of reliability. N-1 criterion arose from one of the first major blackouts in 1965 leading to the formation of NERC to enforce reliability standards upon utilities. NERC operates under the overarching purview of the Federal Energy Regulatory Commission (FERC) which regulates the price of wholesale electricity, service terms, and conditions. Due to a lack of investments in transmission infrastructure over the past several decades, N-1 contingency is no longer adequate due to higher stresses on existing aging components with increased failure rates. Therefore, the system has to operate under N-2 or more failures, which is not easy to accomplish, especially with the rise in volatile renewable energy resources and extreme weather events. About 75% of land area and 90% of electric load in Texas is managed by ERCOT. ERCOT is an Independent System Operator (ISO) for the region that operates a region's electricity grid, administers the region's wholesale electricity markets, and provides reliability planning for the region's bulk electricity system. The neighboring state comprising the electric grid in Oklahoma state is managed by SPP. SPP is an RTO that oversees states in the central U.S. and lies in the Eastern Interconnection having HVDC ties to the Western Interconnection and ERCOT. SPP has its service area extending from North Dakota down to the Texas panhandle. The Texas power system is somewhat unique in that it operates as its own interconnection, independent from larger neighboring interconnections such as SPP which Oklahoma is a part. The ERCOT interconnection ties into the rest of the ac system via these HVDC transmission lines and facilitates a limited amount of power exchange. The majority of generators in ERCOT and SPP are natural gas-fired turbines. Table 1 compares their generation mix as of 2021 [10]. This portfolio of generation is designed to meet the entire electrical demand at any instant, even considering N-1 failures. All generation sources except solar and wind are considered dispatchable. Dispatchable generation carries load even when renewable generation sources like wind and solar resources are unavailable.

Table 1
Generation capacity in ERCOT and SPP.

Fuel type	ERCOT	SPP
Natural Gas	51%	38.9%
Coal	13.4%	24.3%
Wind	24.8%	29%
Solar	3.8%	0.2%
Other	7%	7.6%

3. Sequence of events

3.1. ERCOT

In November 2020, ERCOT released a Seasonal Assessment of Resource Adequacy (SARA) report [11]. The report showed that ERCOT had 83 GW of generation available. It also predicted that under extreme generation outages (forced and maintenance outages) and during an extreme peak load of 67,208 MW (forecast based on the 2011 winter and economic growth forecast in 2020), there will be an operating reserve of 1352 MW as shown in Fig. 3. This indicated a risk of Energy Emergency Alert actions. Later, ERCOT estimated that had there been no load shed during that hour, the actual demand would have been 75,573 MW as shown in Fig. 6. A week prior to the event on February

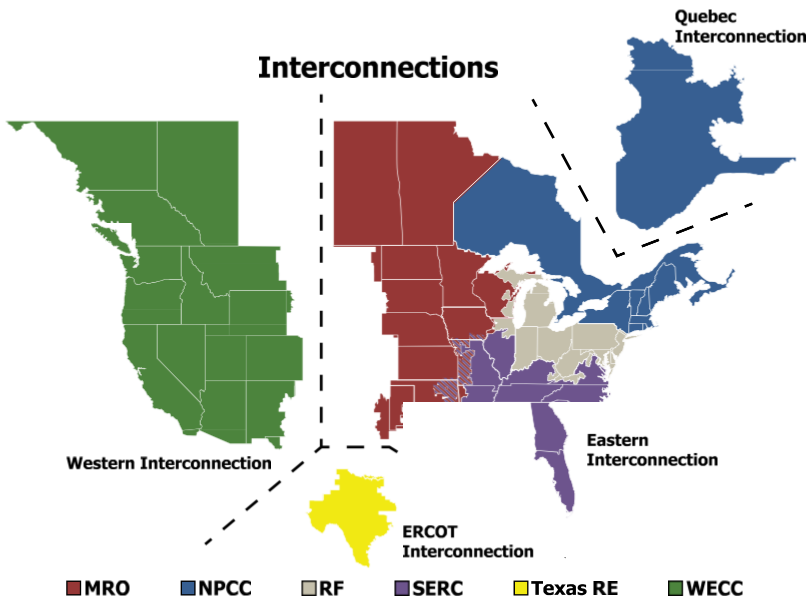

Fig. 2. U.S. electrical grid structure.

9, ERCOT convened a meeting to discuss a wide range of business-related matters. The imminent cold weather events were only discussed peripherally for a short time and did not seem to raise significant concern, other than pointing out that a higher than normal winter peak load was to be expected. (In the aftermath, it was pointed out by utility stakeholders who were present at the meeting that the seriousness of the weather was not properly communicated at large and therefore utilities did not make extensive preparations.)

On Saturday, February 13, 2021, ERCOT issued Emergency Notices for the severe cold weather in the region. This was also the first day that some large generators unexpectedly went offline. A public appeal by ERCOT was issued the next day for energy conservation. Texas is one of the few states that operate their electric grid in a deregulated industry with an open energy market which saw large price hikes imposed on customers (e.g., monthly bills into the thousands of dollars) during the high demand. In the late hours of February 14, generation could not adequately increase to service the demand and the frequency of the grid began to drop. This scenario caused ERCOT to exercise contingency plans to try and bring up additional generation reserves and shed load through rotating blackouts (Fig. 4). These actions failed due to growing generator outages and pre-crisis shutdowns (7.7 GW or 15% of peak crisis demand unavailable due to existing outages). If the frequency had dropped to a sufficient level, automatic load shedding would have occurred [12].

Approximately 15 min after midnight on Monday, February 15, ERCOT issued an Energy Emergency Alert Level 1 (EEA 1) notice, and soon escalated the level at 1:07 am to EEA 2 and again at 1:20 am to EEA 3. This initiated forced load shedding or rolling blackouts in an attempt to arrest the frequency decline. These directives were maintained throughout the crisis until February 19 when the situation started to recover. The lowest and most vulnerable point from a grid operations standpoint was when the system frequency reached a low of 59.302 Hz at roughly 1:55 am on February 15, 2021. There are automatic equipment protection controls that will trip generators if the grid frequency drops to 59.4 Hz or below for more than 9 min. Additional load shedding limited the frequency deviation to 59.4 Hz for 4 min and 23 s on the morning of February 15 (Fig. 5). Thus, the grid was only 5 min away from a complete blackout on the morning of February 15 which would have taken many weeks to restore, as occurred for the 2003 North-East U.S. blackout. Going into the early morning of February 15, generation outages were already high at

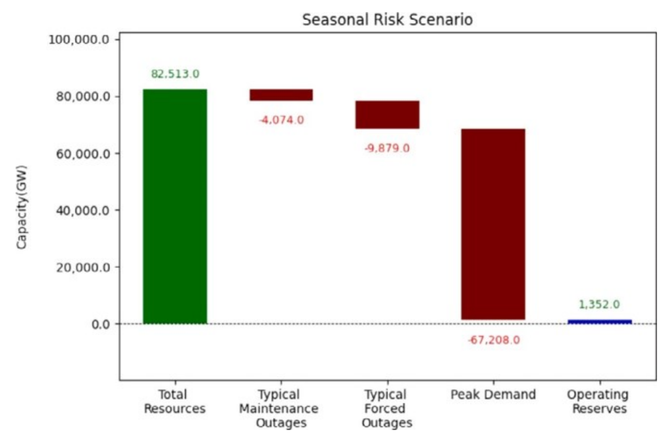

Fig. 3. Waterfall chart of ERCOT winter 2020/2021 scenario report.

roughly 30 GW. By 9:00 am, total outages and derates increased to over 5 GW or roughly 40% of the total installed nameplate capacity in ERCOT. Levels of outages and derates would change throughout the event, only returning to pre-blackout levels on February 19 (Fig. 6).

As the extreme cold weather swept through the state, outages increased. From noon on February 14 to noon on February 15, the offline renewable capacity increased from 15.1 GW to 19.4 GW (+ 4.3 GW) and the total outages of thermal generators increased from 13.7 GW to 31.1 GW (+ 17.4 GW).

3.2. SPP

The North American Winter Storm had a widespread impact across the United States [13]. Like Texas (ERCOT), the entire SPP balancing authority (BA) region was impacted by extremely cold temperatures that lasted days. The storm had a severe impact on electrical and natural gas infrastructure that caused power outages of 2700 MW. The increase in temperature due to storms led to increased electricity use. At the same time, various other factors limited the generators' ability to produce power. Nevertheless, SPP managed to limit service interruptions to a total of about five hours spread over two days. SPP had already started alerting member utilities about possible impacts

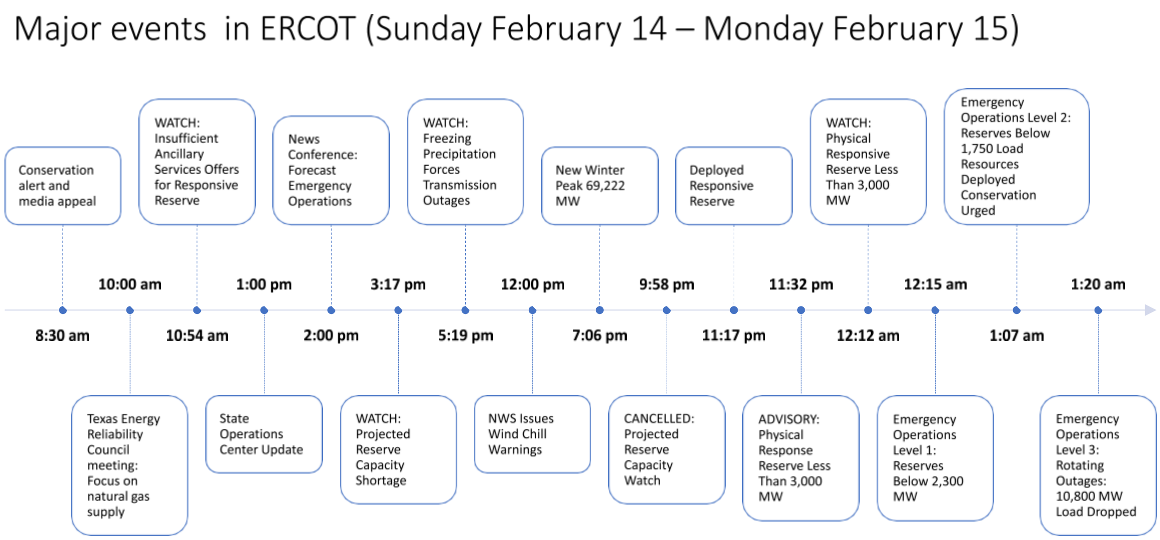

Fig. 4. Critical events (Courtesy of ERCOT).

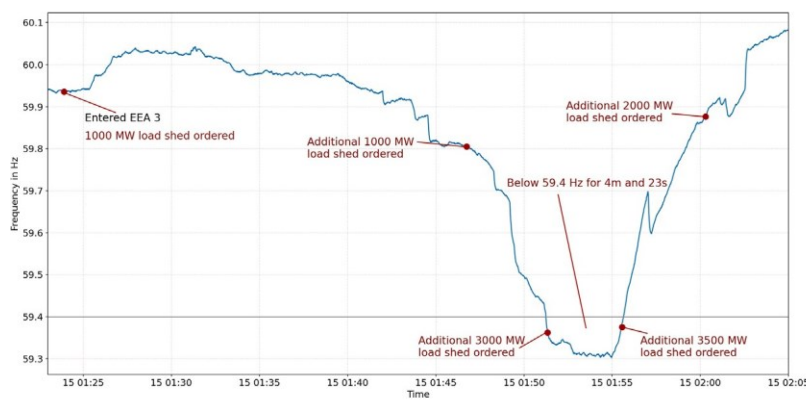

Fig. 5. Frequency instability on the morning of February 15 .

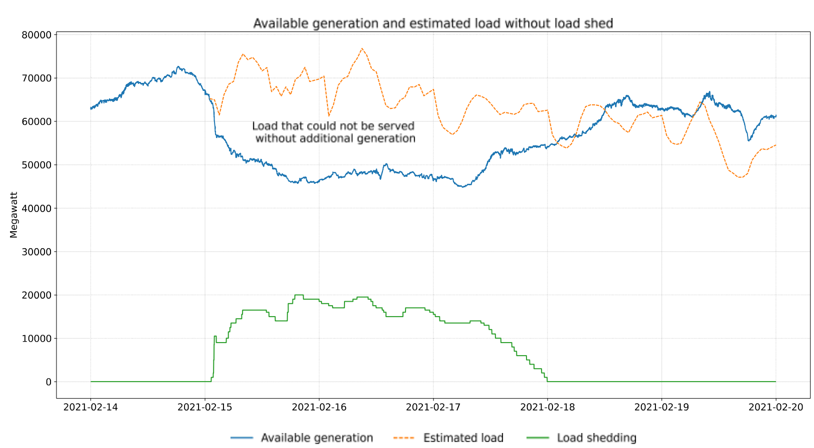

Fig. 6. Reduction in Texas generation availability (Courtesy of ERCOT).

of the winter storm on February 4, and on February 8, and exhibited better resource preparation than ERCOT by ensuring resource commitment startup and run times, and reporting fuel shortages and transmission outages that might impact normal operations. Then on Thursday, February 11 SPP began committing to generating resources using its multi-day reliability assessment process. Instead of committing generation a day ahead, as is standard practice, SPP began sending instructions to generators several days in advance that they would be responsible for serving load for the period Saturday, February 13 through Tuesday, February 16.

As the weather started getting worse, SPP made a public appeal on Sunday, February 14 to conserve electricity due to concerns regarding expected weather and fuel-supply issues. They declared an Energy Emergency Alert (EEA) Level 1 on February 15 at 5 am for the entire region. EEA Level 1 means that all available generation is in use. Public appeals typically follow the EEA Level 1, but SPP decided to implement

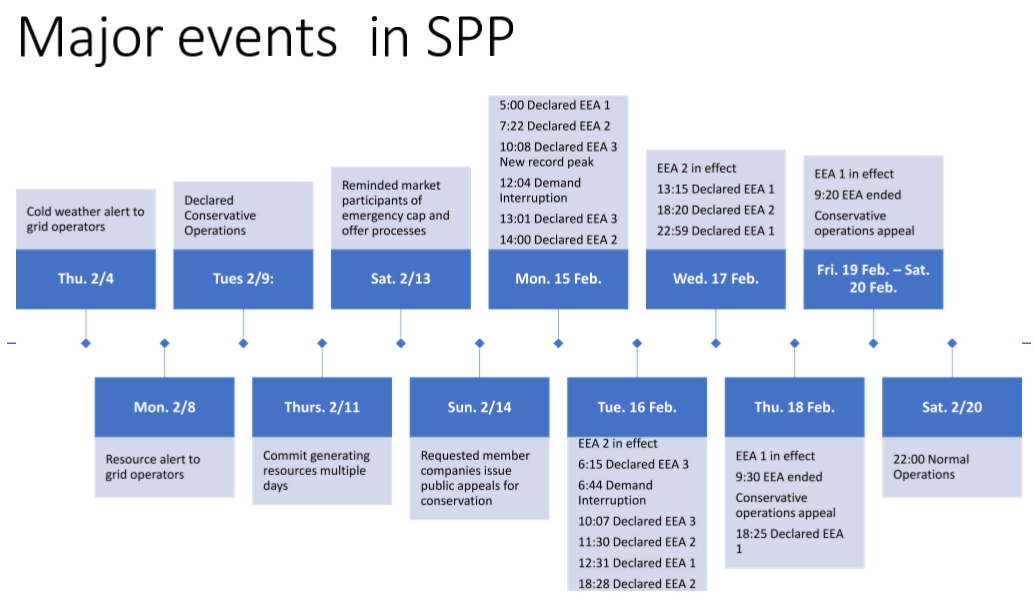

Fig. 7. Key Events in SPP during the Winter Storm Uri.

it early and the decision proved beneficial as the actual load came in under forecast because people responded and used less electricity than predicted.

Shortly after SPP declared EEA level 1, they escalated to EEA Level 2 at 7:22 am. EEA Level 2 means that all available generations have been used up and operating reserves are at risk of dropping below minimum requirements. Typically, SPP directs public appeal for energy conservation at this point. Even after making a public appeal to conserve electricity, SPP set an all-time peak of 43,661 MW for system-wide electricity use in winter across its region at 8:58 am Finally, at 10:08 am, SPP declared its first-ever region-wide EEA Level 3. EEA Level 3 is declared when energy reserves have dropped below minimum requirements and SPP has to find additional generation or lessen region-wide electricity use to keep the system in balance.

Two hours after declaring an EEA Level 3 at 12:04 pm, SPP directed member utilities to deliberately curtail the region's energy use by 1.5%. This controlled interruption of service also called a load-shed event, lasted for 57 min. At 1:01 pm, SPP restored all load, bringing an end to the period of controlled interruptions of services. At 2:00 pm SPP declared an EEA Level 2, having restored minimum reserves, and remained at this alert level for the rest of the day.

Again on Tuesday, February 16, as the region's electricity use rose during the morning hours at 6:15 am, SPP declared a second EEA Level 3. At 6:44 am, SPP directed another controlled interruption of service. The second interruption of service lasted three hours and 21 min and was required to lessen regional electricity use by 6.5%. At 10:07 am SPP restored load, bringing an end to the second and final controlled interruption of service of the winter weather event. Throughout the remainder of the week, from Tuesday, February 16 at 11:30 am until Friday, February 19 at 9:20 am, SPP fluctuated between EEA Levels 1 and 2, de-escalating to Conservative Operations with no EEAs for several hours. Finally on Saturday, February 20 at 10 pm, SPP declared an end to all applicable alerts and returned to normal operations. Fig. 7 summarizes the sequences of events during the event.

4. Root causes

4.1. Generation failure

ERCOT and SPP reported cold weather conditions as the largest category of cause of generation failure. This includes but is not limited to frozen equipment (such as frozen sensing lines, frozen water lines, and frozen valves), ice accumulation on wind turbine blades, snow cover on solar panels, crossing low-temperature limits for wind turbines, and flooded equipment due to snow melt. ERCOT reported the capacity that went offline due to weather-related causes doubled from 15 GW at noon on February 14 to 30 GW at noon on February 15 as reported by ERCOT. The outages were mainly the result of frozen water intakes, sensing lines, wind turbine icing, and the freezing of other general equipment. As freezing weather persisted, many other problems arose such as issues in control and condensate systems that caused plant capacity to reduce (derate) or completely go offline. A total of 167 units faced disruptions due to weather during the event.

The second-largest category of offline capacity was from existing outages of scheduled and planned maintenance, mothballed units, and forced outages that started before February 8. As of noon on February 14, around 8.4 GW of capacity was offline due to these existing outage conditions. The majority of this (7.7 GW) was from coal and natural gas power plants.

The third highest amount of outages was from equipment issues rising from 1.9 GW of outages at noon on February 14 to 5.6 GW a full day later. 146 units were classified as offline due to equipment issues. Reports of unit-specific outage data show that these power plants failed from factors not directly associated with the weather such as clogged sensing lines and stuck valves but due to normal wear and tear. Six black start-rated units were reported among equipment failures.

Fuel limitations account for the fourth most category of outages, with 131 units listing this reason for their outages. Natural gas plants and coal plants were affected the most. Fuel availability issues for natural gas existed even before the crisis began and increased as the event unfolded. No known fuel-related outages were reported for coal on February 14, but on February 15 there were outages of 2.1 GW at 4 pm. For natural gas, lack of fuel, low fuel pressure, and fuel contamination were the major listed outage reasons.

SPP's market typically had about 55 GW of available generation capacity in February. That capacity dipped to roughly 35 GW during the week of February 14, 2021. This 20 GW reduction from available capacity was primarily due to higher than usual fuel-supply deficiencies, wind-turbine freezing, and other challenges associated with operating equipment in extremely cold conditions such as frozen cooling towers, intakes, fuel lines, transmitters, etc. On February 15 and 16, roughly 50% of forced generation outages cited fuel-supply issues as their cause.

In the U.S. southwest, electrical infrastructures were generally built to meet the summer peak load. This was not adequate to handle the

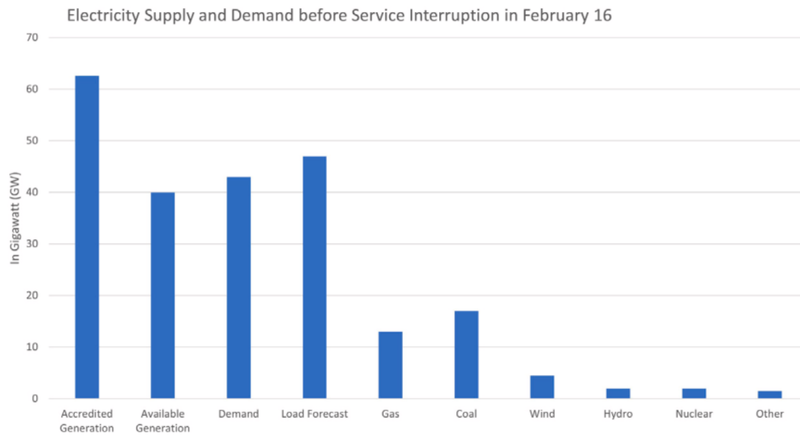

Fig. 8. Generation situation in the neighboring Southwest Power Pool.

severe winter weather events. For example, SPP had a summer peak of 51,037 MW in July 2021 while its electrical infrastructure almost failed when the winter peak was only 43,661 MW even after making a public appeal to conserve electricity.

4.2. Organizational factors

As recognized in the ERCOT Roadmap to Improving Reliability report [14], a massive reorganization and introduction of a new legislature are underway. In the days leading up to the event, there was a lack of direct communication of the weather severity to utility operators and therefore lack of decisive preventative actions. The situational awareness of the grid in terms of knowing what generators were out of action prior to or during the event was poor according to ERCOT's own post-event reports. This also translated into the uncertainty of wholesale prices which are used to incentivize generator owners to make their units available while discouraging consumers from operating high-power items. The COVID-19 pandemic did have some influence in terms of limiting the staffing of senior members in operations centers. Moreover, it has been recognized that overall ERCOT communications must be improved with stronger executive leadership. The even wider issue of an aging workforce and maintaining a steady pipeline of power system specialists still persists. The latest recommendations seek to address this workforce gap with renewed interest in fostering STEM careers.

4.3. Impact of distributed generation and renewable energy

Perhaps the most confusing part of the analysis is the role of renewable energy sources such as wind power. Adding to this, the news media has highlighted several polarizing opinions on whether or not wind and solar power exacerbated the problems. Indeed early ERCOT reports did not fully describe the role of renewable energy sources during the storm due to a lack of information. Since then, more refined data has been published. Firstly, transmission operators use wind forecasts to plan on dispatchable generation capacity from non-renewable sources. It is now known that for this event, ERCOT conservatively forecasted 7% of the state's power would come from wind [11]. Therefore ERCOT made plans to have conventional generators available to entirely serve the load without counting on wind power at all. However, as it transpired, wind power had a significantly larger share of the overall generation just prior to and going into the event. When the turbine blades froze and supporting wind infrastructure failed, wind generation was reduced by almost 50% at the onset of the crisis [8]. Conventional thermal generation, mainly natural gas, could not be brought online for the aforementioned reasons to compensate for the loss of wind. Had the wind not been available, to begin with, more thermal generators would have been already running leading up to the events. The question arises as to if this would have made a difference (i.e., would the additional thermal generation brought online due to no wind have failed anyway?). Further analysis of this is warranted to understand what would have happened if wind power contribution had been closer to the lower expected forecast. Moreover, the role of volatile renewable energy sources during contingencies needs further study. Table 2 points out the key issues related to the renewable energy penetration during the winter storm.

4.4. The role of cross-border transmission interconnections

The power system in the U.S. and worldwide has evolved over the past century from initially being a patchwork of independent smaller networks. Expanding interconnections has afforded many advantages such as a greater ability to economically pool and schedule power transfer from more generator sources, higher reliability through ''strength in numbers'' in more transmission resources (lines, generators, etc.), opening up competitive trading markets, etc. This raises the question as to why Texas has departed from this norm by deliberately limiting the boundaries of its interconnection.

Texas is tied to the Eastern interconnection with two DC ties and has a DC tie and a Variable Frequency Transformer to non-NERC systems in Mexico. The data indicates that for this crisis, the structure of the Texas ERCOT interconnection was a significant factor in the extent of the outage. This is supported by the fact that Oklahoma and other states in the SPP, experiencing similar weather conditions at this time, observed much less severe impacts. The maximum amount of energy that can be simultaneously imported on all of the ties into ERCOT is 1220 MW, with 820 MW of that via the North and East Ties to the Eastern Interconnection. SPP has far more extensive tie-line capacity with the MISO than with ERCOT. SPP's strong network of ac transmission tie-lines with MISO and other BAs, allowed significant amounts of power to be imported during the crisis.

At its worst point, SPP imported power in the range of 4000 to over 6000 MW [15].

Fig. 8 shows that during the worst part of the February crisis, SPP had a 36% loss in the available generation which was mostly compensated by voluntary consumer power conservation actions and importing power from neighbors [13]. SPP met 43 GW of the maximum demand, however, as imports lessened, SPP had to implement emergency procedures to preserve the overall integrity of the grid. The interconnection with other neighboring grids towards the east, which was not under weather-related demands, helped SPP to mitigate the effect of energy emergencies caused by unplanned generator outages and derates.

SPP is moving to expand its interconnections into the Western U.S. Curiously, in the latest ERCOT road map towards resilience document, exploring wider interconnections for Texas was not addressed.

Table 2
Issues of renewable energy penetration.

Affected factors	Issues
Wind	Wind power suffered the earliest outages and derates mainly due to freezing precipitation affecting unwinterized turbine blades and gearboxes. There were 107 outage events impacting 89 individual generation units in ERCOT, 72% of which were wind units.
Solar	Solar capacity continues to be negligible and did not have any significant effect compared to wind. During the crisis, substantial solar irradiance was available that could conceivably supply microgrids, however, their deployment in ERCOT and SPP is minimal.
Stability	Transitioning from conventional rotating generation machines with inertia to inverter-based resources will lower system inertia resulting in less voltage, angle, and frequency stability. Load balancing hence becomes even more critical in crisis events, raising the risk of rotating blackouts.
Resilience	As renewable penetration increases so do their criticality in contributing to system resilience during a storm. While ERCOT and SPP have somewhat diversified fuel sources, the shortfalls of not sufficiently winterizing these units became a single common factor in their unreliable performance.
Planning and Operation	Contingency planning for the event did not anticipate much wind being available, however, as it transpired, it would have helped partially offset thermal generation losses had wind units not frozen.

Table 3
Principle root causes and factors influencing the event.

Failure factors	ERCOT	SPP
Generators and Ancillary Equipment Failures	– Frozen equipment – Scheduled maintenance outages – Broken sensors and control systems – Natural gas fuel supply issues	– Natural gas fuel supply issues – Transmission line capacity congestion – Cold weather conditions
Organizational Factors	– Poor promulgation of imminent storm severity to utilities – Events far exceeded worst-case contingency plans – Limited winterization planning actions followed up post 2011 storm	– Early coordination helped import energy from SPP regions not experiencing high demand – Lack of coordination existed between gas and electric industries to guarantee sufficient fuel
Impact of Distributed Generation and Renewable Energy	– Conservatively forecasted wind power to be 7% of total power – Generation reduced due to icing on wind turbines – Wind generation reduced by 50%	– Same factors, but to a lesser extent than ERCOT
Role of Cross-Border Transmission Interconnection	– Limited import capacity of 1220 MW	– Imported power in the range of 4000 to 6000 MW – Larger grid affording greater stability margins and resilience to disturbances
Electricity and Natural Gas Inter-dependency	– Most natural gas companies enrolled in emergency response program – Forced load shed in natural gas production and processing facilities	– Procurement and deliverability issues due to cold weather – Limited supply and transportation capacity

4.5. *Electricity and natural gas inter-dependency*

The inter-dependency between the electrical power system and natural gas infrastructure was the major factor that lead to the severe power outage. These two infrastructures are critical to the customer separately and their interdependence led to the cascading sequence of power failures. In ERCOT, natural gas companies' decision to enroll in emergency response programs made this interdependence more serious. About half of the installed generation capacity is dependent on natural gas. In addition to this, most of the natural gas production and processing facilities were not identified as critical loads or protected from manual load shedding.

ERCOT did not expect that a firm load shed would lead to power outages in natural gas production and processing facilities. During a time when more generation was desperately required, ERCOT was unnecessarily forcing load sheds to critical natural gas supply affecting the delivery to the natural gas-fired generating units. The extent of power outages caused by unnecessary firm load shed remains unknown.

A retrospective analysis shows a lack of access to natural gas was the largest contributing factor to the severity of the event and it establishes the need for better coordination and communication between the gas and electric industries moving forward. In particular, additional early communication of potential severe conditions and the forecast of high demand for natural gas could have provided both industries with useful preparation time.

For SPP, extreme cold weather across parts of the region resulted in natural gas procurement and deliverability issues. The available natural gas for consumption by electric generation and other customers was limited by the capacity of the supplies and transportation provided by the gas pipeline system.

The heavy reliance on natural gas and inter-dependency with the electrical system is the most influential factor from a standpoint of resiliency and reliability of grid infrastructure. Natural gas generation experienced an average of nearly 18 GW of forced outages during February 16, and of those outages, nearly 75% cited lack of fuel supply as the cause. On average, over 48% of all forced outages experienced during the week of the event were caused by fuel supply issues. Table 3 summarizes the root causes discussed in causes that led to the events in ERCOT and SPP.

5. Concluding remarks

This paper summarizes the events and contributing grid operational factors to the U.S. Southwest power system crisis. The circumstances of the disaster are contrasted with parallel events occurring in neighboring interconnections such as the SPP for Oklahoma which experienced less serious impacts. Fundamental questions are raised on long-standing system design criteria such as the rationale of interconnections, and the role of renewable energy. The study comments on organizational issues from the RTO/ISO level down to individual utilities such as lack of situational awareness and effective communication before and during the crisis. The results summarized in this paper were obtained from published reports by ERCOT, SPP, news articles, and other related research articles. There is a lack of more granular data at the component and system levels which will hinder researchers from conducting a deeper analysis with detailed power system simulations. For example, highly protected transmission network data would be necessary to conduct a more thorough failure mode analysis. They would require the cooperation of senior management of multiple entities including ERCOT. A possible alternative is using synthetic grids created by researchers that do not contain sensitive information but are representative of complex power system behavior. Likewise, similar challenges exist in integrating other key infrastructures such as gas supply lines, water supplies, and transportation.

CRediT authorship contribution statement

Srijana Shrestha: Methodology, Validation, Resources, Writing – original draft, Investigation, Visualization. **Vinushika Panchalogaranjan:** Writing – original draft, Resources. **Paul Moses:** Conceptualization, Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Paul Moses reports a relationship with National Science Foundation that includes: funding grants under NSF Award No. OIA-1946093

Data availability

No data was used for the research described in the article.

References

[1] FERC, Report on Outages and Curtailments During the Southwest Cold Weather Event of February 1-5, 2011, Tech. Rep., FERC, NERC, 2011, URL www.ferc.gov/sites/default/files/2020-04/08-16-11-report.pdf.

[2] P. Aldhous, S.M. Lee, Z. Hirji, The texas winter storm and power outages killed hundreds more people than the state says, 2021, Buzzfeed News URL www.buzzfeednews.com/article/peteraldhous/texas-winter-storm-power-outage-death-toll.

[3] NOAA National Centers for Environmental Information (NCEI), U.S. Billion-Dollar Weather and Climate Disasters (2022), 2021, http://dx.doi.org/10.25921/stkw-7w73, URL www.ncdc.noaa.gov/billions/.

[4] K. Hayhoe, D. Wuebbles, D. Easterling, D. Fahey, S. Doherty, J. Kossin, W. Sweet, R. Vose, M. Wehner, Our changing climate, in: D. Reidmiller, C. Avery, D. Easterling, K. Kunkel, K. Lewis, T. Maycock, B. Stewart (Eds.), Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II, U.S. Global Change Research Program, Washington, DC, USA, 2018, pp. 72–144, http://dx.doi.org/10.7930/NCA4.2018.CH2.

[5] T. Mclaughlin, S. Kelly, Why Hurricane Ida crippled the New Orleans power grid, 2021, Reuters URL www.reuters.com/business/environment/why-hurricane-ida-crippled-new-orleans-power-grid-2021-09-04/.

[6] O. Comstock, Hurricane Ida caused at least 1.2 million electricity customers to lose power, U.S. Energy Information Administration, 2021, URL www.eia.gov/todayinenergy/detail.php?id=49556.

[7] NERC, ERO enterprise | regional entities, 2022, URL www.nerc.com/AboutNERC/keyplayers/Pages/default.aspx. (Accessed 3 January 2022).

[8] ERCOT, Company Profile. URL www.ercot.com/about/profile.

[9] SPP, About us. URL www.spp.org/about-us/fast-facts/.

[10] ERCOT, Fact Sheet November 2021, Tech. Rep., ERCOT, 2021.

[11] ERCOT, Seasonal Assessment of Resource Adequacy for the ERCOT Region (SARA) Winter 2020/2021, Tech. Rep., ERCOT, 2020.

[12] ERCOT, ERCOT Nodal Operating Guide, 2021, pp. 2–36, Ch. Section 2.6.

[13] Southwest Power Pool, Comprehensive Review of SPP's Response to the February 2021 Winter Storm, Tech. Rep., Little Rock, Arkansas, USA, 2021, URL www.spp.org/markets-operations/current-grid-conditions/2021-winter-storm-review/.

[14] ERCOT, Roadmap to Improving Grid Reliability, Tech. Rep., ERCOT, 2021, URL https://www.ercot.com/files/docs/2021/10/18/ERCOT_Roadmap_October_15_2021_Update.pdf.

[15] Federal Energy Regulatory Commission, The February 2021 Cold Weather Outages in Texas and the South Central United States, Tech. Rep., North American Electric Reliability Corporation, 2021, URL www.ferc.gov/media/february-2021-cold-weather-outages-texas-and-south-central-united-states-ferc-nerc-and.