Extreme Weather and Regional Grid Resilience

Lessons Learned from
Texas Winter Storm Uri

siemens-energy.com

Dear Readers,

We are in an era of unprecedented change. Not just one of rapid innovation, but one of substantial re-invention of our historical infrastructure and our experiences. Fifty years ago, we engineered solutions to mitigate air quality to combat lake acidification, acid rain, and persistent air quality problems in the major urban air centers. To that end, we were incredibly successful.

Today we are faced with the challenge of maintaining an aging power grid against storms of increasing intensity and scale. As recently as September 2021, a single major storm caused massive damage across nine states to multiple utilities. Millions were left without power in sweltering heat and flooded homes.

Richard Voorberg
President, Siemens Energy NA

In February 2021, the state of Texas also experienced widespread power system failures that revealed significant weaknesses in regional grid resilience. Siemens Energy testified at the Texas Legislature as an expert source on the winterization of power and transmission systems and what could be done to prevent widespread power outages during future inclement weather conditions.

We took those recommendations a step further and pursued additional research on how extreme weather conditions, including hurricanes and other possible natural disasters, impact grid resiliency in Texas. The result is this white paper, which focuses on how companies like ours can work with our customers and regulators to improve regional grid resiliency for the future wellbeing of the communities where we live and work.

While this paper is specific to lessons learned from Texas Winter Storm Uri, we also hope it provides insight on how Siemens Energy is devoting considerable resources to adapt to the rapid changes occurring in our energy ecosystem. Some of these innovations involve new technologies such as energy storage, decarbonization, and digitalization. Others involve the adaptations and improvements of established technologies such as advanced gas turbines that can operate on hydrogen and offshore wind turbines. All of them concentrate on how we reduce the emissions of heat-trapping gases such as CO_2, which are implicated in the intensity of recent storms.

Reliable, resilient grids will be the bedrock of the energy transition. In this review, we propose steps of how to balance the demand for power using the established delivery systems against what many consider new and powerful sources in nature. It will be an ongoing journey. But we believe, by working together with customers and policy makers, we can be successful in meeting the challenges that the future lays before us.

Table of Contents

“The confluence of both increasing complexity and greater risk will demand far more oversight and investment than in the past.”

1. Executive Summary

The nation’s need for reliable energy supplies is greater than ever. The power generation element has moved far beyond the traditional roles of heating and lighting expanding into large-scale financial, communication, and specialized industrial manufacturing. Almost every industry expects to be impacted by a shift from direct human supervision to machine supervision of activities (e.g., long-haul trucking). Furthermore, the increasing impact of electrification on industrial processes, increasing private demand (e.g. EV’s) and increasing share of fluctuating renewables fed into the system heavily impacts the infrastructures even further. Such a paradigm shift will increase the demand for even greater supply resiliency.

This is occurring at a time when the scientific community is warning that weather extremes, which are similar to what we have recently been seeing, will worsen. The confluence of both increasing complexity and greater risk will demand far more oversight and investment than in the past. Studies presented here highlight how some extreme weather events will impact a power grid.

The widespread power system failures that occurred in Texas during February 2021 revealed significant weaknesses in the design and operation of the power system within the Independent System Operator (ISO) for Electric Reliability Council of Texas (ERCOT). ERCOT (also known as Texas Regional Entity) is one of six reliability council regions in the continental United States. Beyond ERCOT’s boundaries, there were few incidents of noticeable power disruption and much shorter durations despite experiencing similar meteorological conditions. In addition, concerns about system reliability were raised three months prior when power outages were a potential in the western part of ERCOT.

ERCOT’s system was similarly stressed nearly a decade earlier when ambient temperatures were comparable although not as severe. One difference between the 2011 and 2021 weather events is the substantial growth in non-dispatchable energy supplies. By 2021 extreme weather was affecting a much larger portfolio of renewable assets.

Extreme weather events appear to be occurring more frequently, and with greater intensity (Appendix A). Also, we note that our assessment of ERCOT suggests that extreme cold events may present more operational challenges than severe storms or hot weather. A large-scale storm such as a hurricane can be accommodated by the existing gas supply and generation infrastructure. Future safe operations need to make accommodations for these extreme cold events as they could markedly impact equipment performance. In response to these obvious new stresses, the following recommendations are offered as blueprint to prevent systemwide failures. Because weather is the dominant factor in the interruption of power in nearly every ISO, the concepts discussed here can potentially be universally applied to every region of the U.S. and grid systems beyond. Of course, other natural disasters like fires and man-made disasters like cyber attacks need to be studied cases-by-case and proper recommendations to be developed.

A critical finding we note is that the exponential growth of wind (and solar) has reached a level where the renewable generation can, at times, exceed the total minimum demand for electricity within ERCOT. If these renewable resources are fully utilized, it could force a significant volume of dispatchable resources (gas turbines, combined cycles, thermal plants, etc.) to idle, or go offline completely. With restart times that could last between one and three hours, the idling of a substantial inventory of dispatchable resources could result in a serious shortfall in generation.

One solution to this mismatch between renewable and dispatchable generation is to improve the response time of both systems and bridge the time by grid stabilizing elements. A combination of grid stabilizers with super-fast, short-term and long-term response times for renewables, and faster starting and ramping of gas turbines and internal combustion engines would seem a logical choice. Of course Gas Turbines can be forced (e.g., via regulation and/or financial incentives) to operate on low load to improve response time.

For more specific recommendations, we focused our comments on four topics: Power Generation (including Transmission & Distribution), Fuel and Energy Supply (more specifically gas supply), Grid Stabilizing Elements, and Regulatory Changes. **These 15 recommendations include:**

1) **Auditing of critical infrastructure elements,** including modeling of how changes or improvements affect the entire system.

2) **Cold weather (or freeze) protection of assets,** including air dryers to remove moisture that can freeze in the plants control air systems.

3) **Improve on the multi-fuel capability for gas turbine operation in ERCOT.** Currently only a handful of combined cycles are dual-fuel capable.

4) **Freeze protection within the gas turbine enclosure,** including insulation and heat tracing. Heated steam turbine enclosures for fast start.

5) **Heat tracing and insulation** of all water or steam filled piping.

6) **Freeze protection measures** in susceptible gas production fields.

7) **Expand regional natural gas storage fields** near major load centers to be able to supply natural gas to power generators. Daily Deliverable Volumes should be expanded in the West and Southeast, and Working Gas Storage (as well as Daily Deliverable Volumes) should be increased in the Northeast and South.

8) **Prioritize Gas Delivery Infrastructure** (Gas Gathering Systems, Gas Plants, Pipeline Compressor Stations, and Gas Storage Facilities) in transmission and distribution level load shedding schemes, particularly in cold weather events.

9) **Winterization** to ensure gas supplies are not interrupted by cold temperatures.

10) **Mandate Public Interest Override** in Demand Response Contracts for Gas Delivery Infrastructure to prevent the loss of critical infrastructure, particularly in cold weather events.

11) **Set up the asset condition monitoring** (e.g. by Drones) on a regular base.

12) **Improve ERCOT interconnection** to adjacent regions, even if only periodically by fully controllable additional grid interconnectors (e.g., HVDC).

13) **Ensure that the laterals which deliver storage gas into the major inter-state and intrastate pipeline systems are adequately maintained** and are exempted from load shedding to ensure they do not render available stored gas undeliverable.

14) **Replace wooden poles** with structures sufficient to handle conditions more severe than the historical norms. Experience has shown this to be an effective resiliency strategy.

15) **For severe flooding and deep snow, elevate equipment** (or install barriers) and utilize higher support structures, build special drainage system, or wall system, and seal control rooms and substations.

1.1 Power Generation Enhancements

Resilience

Impose standardized maintenance and inspection metrics throughout the system. Inspections primarily focusing on key standards for hardware robustness (e.g., insulation of water lines, sensors in key locations for equipment temperature monitoring). Establish a centralized data collection and information reporting system with smart alarming (or AI) to monitor and report on power generators that are critical market operations.

Energy storage and supply

Expand regional gas storage reservoirs to levels capable of supplying all gas fired generation within 50 miles of the storage basin for a period of up to ten consecutive days. (Gas storage resources are discussed in Appendix B).

Cross-regional connection

ERCOT is isolated, with limited connection to other regions and it remains unregulated at the federal level. However, ERCOT could maintain periodic connection to adjacent NERC regions, without fully interconnecting to them. This would allow nearby resources to act as temporary energy storage, accessing them in rare occasions.

Backup generation

The number of end-users that are in situations of "must-have" electricity is growing rapidly. These include hospitals, financial institutions, data centers, water treatment plants, natural gas producing and processing facilities and military reservation to name a few. These groups often require some degree of uninterrupted energy supply. If it isn't available over the wires, they may access the pipeline network, or a separate temporary fuel storage system. In a recent example, some supermarkets access to natural gas through a pipeline distribution network has been preferred because of the perceived reliability of the gas supply. The stability of this secondary support network is routed in the security of the primary supply network. Siemens Energy proposes that regional gas storage reservoirs with compression would ensure the supply of these energy needs.

Transmission & Distribution

The T&D network is the highway to moving electricity across a region, and across the country. As it turns out, these networks are uniquely vulnerable to severe storm damage. In fact, perhaps as much as eighty percent of all outages are related to T&D problems amplified by more extreme weather. Hardening this network is a key to maintaining a resilient power delivery system.

As noted in the Appendix C, minimum demand within ERCOT has grown over the last decade, from approximately 22,800 MW in 2011 to 27,800 MW in 2020. Over that same interval installed wind capacity grew from 9,000 MW to over 30,00 MW (36,000 MW of wind and solar). What role, if any, this overabundance of non-dispatchable supply that now exceeds the regional minimum demand is a subject worth further evaluation. It may be necessary to establish non-dispatchable curtailment protocols to protect the entire system.

1.2 Fuel Gas and Energy Supply

The energy supply system within ERCOT is tightly interwoven. As the storm revealed, the performance of one (e.g. the gas supply) can markedly impact the overall system performance. Updates and improvements are noted here.

Natural Gas Storage

Expand regional gas storage reservoirs to levels capable of supplying all gas fired generation within 50 miles of the storage basin for a period of up to ten consecutive days. In some cases, this may necessitate an increase in working daily delivery of gas rather than an increase to total reserves.

Texas' ability to utilize stored gas during a weather event will become increasingly important as production levels decline over time. Weather events impact the ability to deliver produced gas to market, both for production and transportation companies. Additionally, Texas' gas supply and demand are not naturally co-located, with the majority of production in the West and South, and the majority of demand in the Northeast and Southeast. Fortunately, there are many gas storage areas near the major load centers. Expanding regional gas storage will shorten the path to market and will reduce the number of potential failure points in the gas delivery system. Without a secure fuel supply, the recommended improvements to power plant availability may result in no net gain to the energy system.

Prioritization of Gas Delivery Infrastructure in Load-shedding Schemes

As highlighted by the Winter Storm Uri Natural Gas Analysis commissioned by the Texas Oil and Gas Association, loss of power was the leading cause of production curtailment during the storm. When "industrial consumers" are shed without distinction, the very assets supplying the fuel needed to increase the state's power supply are cut off. This causes a negative feedback loop, as curtailments to fuel supply result in curtailments to power delivery, which result in further curtailments to fuel supply and so on. Specific assets to protect should include gas gathering systems, gas processing plants, gas pipelines, and gas storage sites.

Public Interest Overrides in Demand Response Contracts

In some cases, producers or transporters have entered into demand response contracts resulting in an unintended encouragement to electricity providers to shed load when that load is critical to the public interest. Demand response contracts for gas delivery infrastructure should be required to include no-fault public interest overrides, in which power suppliers are prevented from shedding gas delivery infrastructure. We encourage regulators and state legislatures to consider implementing such back stop mechanisms.

LNG

Above ground gas storage facilities (LNG) have been used for decades, and new LNG exporting facilities are under development. While the regasification and deployment of LNG for power generation is less feasible than gas stored regionally in reservoirs, the utilization of LNG storage should be revisited periodically as exports (and therefore installed storage capacity) increase.

1.3 Transmission and Distribution Improvements

ERCOT's grid has evolved substantially in the last 20 years. The growing number of decentralized renewable sources place new demands on the existing power grid. Meanwhile dispatchable resources are the primary resource to compensate for the power intermittency of wind or solar.

Reliable supply

For equipment to function reliably even under extreme environmental conditions, the product must be designed for this load as well as the entire system design. Wind, heavy rain, snow and ice have different effects and must be considered individually and sometimes concurrently. In addition to the design, the maintenance status of the equipment must be appropriate to ensure safe operation. In this regard, modern equipment requires relatively less maintenance and is therefore advantageous. Increasing digitization solutions offer operators convenient opportunities to coordinate and individually plan maintenance cycles in order to withstand safe operation even in extreme situations.

Fast response resources

While the grids are fundamentally changing in terms of power generation, the feed-in of renewable energies and steadily increasing demand, the power quality and dynamic grid stability are endangered by less synchronous power generation. Operators are facing higher demands for a large flow of electricity, cheaper electricity delivery and higher reliability. Flexible AC Transmission Systems (FACTS) are a perfect solution for increasing the reliability of AC networks, ensuring stability and increasing transmission efficiency. Voltage fluctuations due to lack of short-term generation or consumers and the associated network failures are prevented; network resources are optimally used and load-related disruptions are minimized.

SVC PLUS® (Static Var Compensator) help when fast voltage regulation is required to reliably perform voltage stabilization and control tasks. Different control concepts can be combined with a wide variety of configurations for individual applications. They increase network reliability by supporting failure elimination and thus reducing the risk of blackouts. They improve the power factor by dynamically providing reactive power for a short time and can compensate for the imbalance between the three phases.

Since the feed-in of electricity from renewable sources continuously replaces conventional synchronous electricity generation, the network frequency becomes more sensitive due to the reduced proportion of rotating machines. Network operators are now faced with the challenge of providing sufficient system inertia for synchronous generators with high rotating masses in order to stabilize the network. An SVC PLUS® Frequency Stabilizer can solve this challenge, as it is able to emulate the system inertia by feeding a high active power into the grid when required. In addition, it offers voltage support through reactive power compensation. After a fault, the frequency can only be stabilized by an inertial response from generator-turbine sets.

Less rotating machines lead to shrinking instantaneous reserves, which increases the risk of critical frequency values being exceeded. This can lead to a load rejection or a blackout. Synchronous condenser for voltage control offers network stability e.g., for transmission networks with a high proportion of renewable feed-in by providing short-circuit power, inertia, and reactive power compensation.

Meshing for safe operation

Another factor that plays a key role is a weak connection to resources outside of ERCOT. ERCOT has its own grid region, relatively isolated from the large networks on the US east and west coast. Power generators were isolated, making it difficult to import electricity during the crisis. In addition, decentralized energy systems and the associated uncontrolled power flows pose challenges for the existing AC grids. Thermal overloads in the lines and a growing number of cases in which frequency and voltage come critically close to acceptable range limits, or even exceed them, threaten grid stability and the transmission infrastructure. UPFC PLUS lets you get the most from your existing grid capacity while maintaining maximum protection, reducing the risk of power failures, and minimizing redispatch efforts.

To stabilize the network, a high degree of meshing is necessary. This is how several generations feed-in and a failure of a single one does not affect the supply dramatically. The coupling takes place at strategic network nodes in the high voltage side with either AC systems or HVDC systems. Something similar can be done through the connection using MVDC Plus® systems, which provides load flow control, long distance transmission, increased feed-in for renewables, transmission autonomy and grid connection.

Prepared for the unexpected

Pretact® Grid resilience concept enables network operators to react in advance. Even all the mitigations to avoid failures is considered, it is recommended to plan for the unexpected. Such measures can include to have versatile spare units or mobile solutions available which can be transported easily and installed very quickly in case of emergency.

All these products and solutions are part of modern power transmission networks, which enable reliable and safe operation at extreme weather scenarios even with a high proportion of renewable energy.

1.4 Regulatory Updates

Texas regulators are hard at work to implement measures recently signed into law that will avoid a repeat of the devastation brought about by the winter storm in February 2021. The intent of these new regulations is to give ERCOT a stronger mandate and enforcement authority.
(ERCOT, 2021).

Prepare the Texas energy system to address the overall impact of climate change, not just one or a few extreme weather phenomena

Winter storm Uri was a first-of-its-kind weather phenomenon in Texas. It was more impactful than its predecessor in 2011, and it is not unreasonable to think that this type of winter phenomenon can happen again with equal or more intensity. On the other hand, summer temperatures in Texas are trending upwards and hurricane formations are on the rise. In fact, 2020 saw the most active hurricane season on record.

An all-encompassing review of markets and technologies is critical to making the Texas energy system more resilient. Historical weather data can only go so far with existing assumptions, and the trend towards more intense and perhaps more frequent extremes may call for fresh assumptions. The right partners, models and tools are key to project trends and give effect to mitigation strategies, optimize investment with the right technology choices, and ultimately drive grid resilience, thereby enhancing reliability for all Texans.

Be outward looking - collect best practices from around the world

The three largest cities in Texas – Houston, Dallas, and San Antonio – are partied to sister city networks across the globe. In fact, at least 35 cities in Europe, Asia and Australia are “sisters” to the three Texas cities, forming a network which promotes understanding, dialogue, cultural links, and cooperation.

It would be worthwhile to tap into these existing networks, and possibly expand the scope of collaboration to uncover potential best practices in terms of climate action.

Develop regulatory actions to overrule market mechanisms in emergency cases and potentially declare some units as reserve to prescribe their operations.

Incentives to provide reliable power are critical

Historically, ERCOT’s focus was mainly on the affordability of power supply to Texans. Today, that focus has changed to reliability first. Regulators want to shift away from a crisis mode of management towards establishing incentives for stakeholders that reward reliable power supply, as part of a total market overhaul. One example of such a shift is the activation of more reserve power earlier rather than activating less reserves later, i.e., once a freeze or another weather phenomenon has already happened. The systems and details of such incentives are still being formulated by the Public Utility Commission and ERCOT. Another aspect would be to require market participants to have active fuel supply contracts for at least 30 days. Significant penalties for non-performing assets should be a component market rules.

Tariffs

The ISO should review any rate structure that incentivizes critical energy industries to disconnect from their system unless those industries have backup generation, alternative energy sources, or can demonstrate that their voluntary load shed does not impact ISO power generation or grid stability.

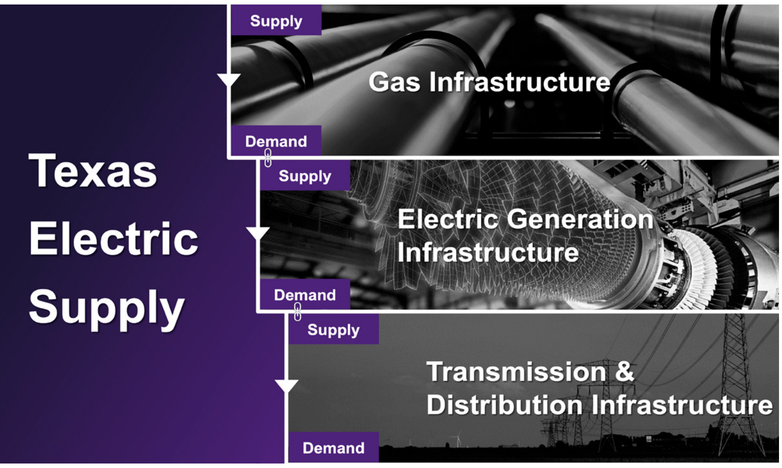
Furthermore, recently passed law requires the weatherization of all generation, transmission, and natural gas facilities and pipelines within Texas. Failure to comply with such weatherization requirements can result in significant financial penalties. ERCOT could also evaluate implementing some sort of capacity market (i.e., operators rewarded for the ability to ramp up power, even if no kWh are produced). At the end, a proper balance of costs and benefits should be considered to develop a resilient system in ERCOT.

Adopt digitalization for more effective weatherization

ERCOT has advised that summer weatherization checks were conducted for the first time in 2021. In addition, policies are being developed which sets several standards for weatherization to ensure the resilience of assets over time. A key observation is that there is less time to take assets offline for regular maintenance and service, especially during the hot summer days and coldest winter periods. One of the considerations of the Public Utility Commission and ERCOT is to require plants to remain operational and provide services under the 95th percentile of extreme weather scenarios. For example, the plants would have to function during 95% of extreme high or low temperatures that might occur. Remote monitoring using digital capabilities should be deployed to provide information at a point and deliver indicators that inform smart choices about the availability of assets, especially during time of extreme heat, cold or even hurricanes.

2. Background

The goal of electricity delivery is to be reliable, affordable, and a growing emphasis on sustainability. The reliability aspect is becoming more challenging as the world is becoming more complex with larger demands in a digital world (IoT, e-commerce, finance, server operations and data communications, etc.). Additionally, there is likely to be greater threat to established power delivery systems with what appears to be carbon-induced climate change. The cumulative buildup of CO_2 in the atmosphere has the potential to magnify extreme weather conditions, including drought, hurricanes, intense precipitation, and flooding.



These extremes have been observed with increasing frequency, duration, intensity, and geographical size.

The energy supply chain rests on three critical components as shown below all of which are interdependent with one another and have to balance their own supply and demand continually: Gas infrastructure, Electric (power) Generation, and Transmission & Distribution.

These elements are the base support in a modern economy. In the United States, the power grid is divided into a number of power generation regions, nominally noted as Reliability Councils (such as SERC)[1]. In some ways they are sufficiently insulated from each other so as to create a measure of hazard containment, although this was not by design but rather reflected the location of the early utilities that evolved to supply local industrial customer needs.

ERCOT is one of six Regional Reliability Organizations (RROs) in the continental United States[2]. It stands almost completely isolated from the Eastern and Western Interconnection and is also asynchronous to each of the regions. It is not the largest power grid, but it has one of the largest renewable resource bases in the nation, a base that continues to grow rapidly.

[1] There are also many more subcategories of power delivery in municipal generation and cooperatives.

[2] Hawaii and Alaska also have a regulatory body overseeing the power markets.

ERCOT, operating within the state of Texas, plays an outsized role in the total GDP of the U.S. economy. It is a major oil and gas producer, a center for refining and petro-chemicals, a center for advanced technology, and an export hub to other economies.

All the nations power grids within the continental system have encountered significant outages at some point in time. Since 2011, 2,338 grid disturbances were reported by the U.S. Department of Energy (Energy, 2021). Most of these grid disturbances have been weather related. Human factors and equipment failures have played a role in some notable system failures, but ultimately weather has played the dominant role.

In February 2021 ERCOT was struck with a system-wide weather-based assault on mostly two of the three supports of the supply base. The February 2021 outage was unprecedented for ERCOT and concentrated over almost the entire service territory (although not all of Texas). This was clearly defined in the post-mortem carried out by ERCOT and shown in Figure 1. The weather impacts were sufficient to affect virtually all power generation, natural gas supply, and the Transmission & Distribution systems. (NERC, 2021)

Siemens Energy was able to remotely monitor some impacts of the storm. Our Power Diagnostics Center monitors gas turbine combined cycles within ERCOT. During the storm, some of the following operational issues were detected.

Units either tripped or could not start due to:

- Iced inlet air filters
- Freeze in LP drum level columns
- Non-functioning NG blending valve
- Loss of condensate return
- Fire in turbine enclosure and fuel oil
- HRSG tube leak
- Generator exciter fault
- GT blade path spread

The weather was also a factor in the problems with energy delivery that occurred in the same region almost exactly a decade earlier. And cold weather also surfaced as a concern approximately three months prior to February.

On October 28, 2020, ERCOT issued a weather-related advisory to the city of Abilene due to expected cold temperatures. While advisories are not uncommon, the concern was over the cold temperature in the region, even though temperatures were not expected to reach freezing[3]. The reliability concerns in October 2020 may have been an early indication of problems unresolved from the 2011 winter cold wave.

As a result of the previous deep-freeze in 2011, freeze recommendations were put in place to weatherproof and winterize energy systems. System-wide modifications after the 2011 event were insufficient to accommodate the impact of the even colder 2021 winter storm.

Net generator outages and derates for natural gas generators by cause

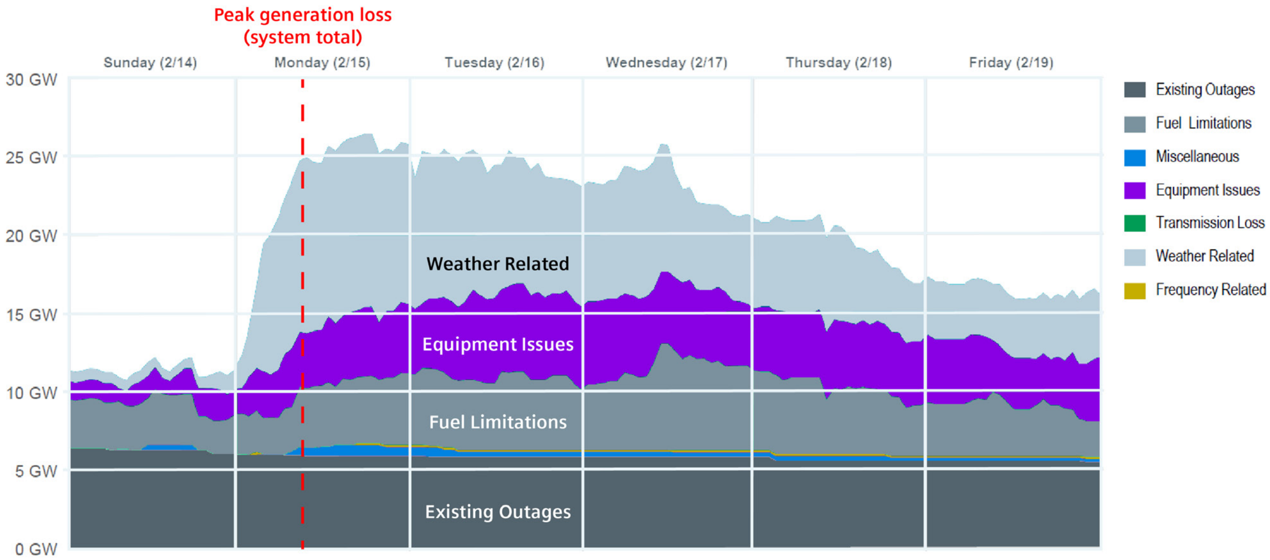


Figure 1 Factors contributing to ERCOT system failures

[3] ERCOT: 'Abilene citizens should expect rotating outages of power' - MDMH Abilene (mdmh-abilene.com)

2.1 Power Generation: A key in the supply triad

The energy chain of custody begins with the fuel resources required to produce electricity, the energy conversion (or storage) system, and then the transmission and distribution system. Failures or disruptions anywhere along the value chain can result in disruptions that might range from an annoyance to life-threatening situations. There is some level of redundancy to support the system where backup generation or local energy storage is available, but these were clearly not sufficient.

For the power generation phase, the technology choices for a stable, effective power delivery system include:

1) Reliable and available generating capacity.
   a. Nuclear, gas turbine, and thermal generation.

   b. Access to backup resources during critical shortage periods.

2) Low cost, reliable delivery of raw materials.

3) Robust transmission and distribution.
   a. Including redundancy to accommodate individual or multiple component failures.

   b. Ability to rapidly isolate key faults within the system.

   c. Offer support to key infrastructure components during system stress. (Hospitals, water treatment facilities, fire, and rescue, etc.)

The list, however, is somewhat commoditized. It suggests that packets of energy can be in reserve and simply delivered to the critical end user as needed. Such a scenario is not possible, even with small power systems, or modestly sized energy storage devices. The complexity of the Transmission and Distribution system, and who has responsibility for the components can make it nearly impossible to determine how the system will respond under a great deal of stress and who has ultimate responsibility for actions needed to prevent system collapse (e.g., open breakers at key junctions).

For power generation, there is a standard menu of selections for energy conversion devices (e.g., gas turbines, steam turbine, reciprocating engines, etc.). One element that deregulation introduced was the exposure to the market of competitive options for energy supply. In the regulated market, the emphasis was typically on oversight of the return on investment of the regulated entity. Arguments against this model stressed that it encouraged over-investment. Capital purchases could simply be passed on to the rate payer if sufficient evidence could support the acquisition. Switching to a deregulated market allowed new entrants into the market, but the focus shifted away from the price of electricity to the consumer, and how investment costs were recovered. The new model would emphasize competition, with participants, and Original Equipment Manufacturers (OEMs) focusing on a different set of project benchmarks, such as:

1) Capital cost

2) Unit efficiency

3) Tax benefits, and

4) Fuel flexibility

Upon their initial introduction, one of the key values of the gas turbine technology was operation across a broad fuel quality range[4]. Gas turbines are capable of operation on hydrogen, gasoline, kerosine, natural gas, and propane. On the island of Puerto Rico, Siemens (then Westinghouse) installed two large frame machines that could run on 1) natural gas (from LNG), 2) diesel fuel, and 3) propane. Being isolated on an island, fuel redundancy was crucial for continued operation. While being capable of operating on three fuels demonstrated a degree of resiliency, it also introduced a significant amount of complexity. Most power systems do not make use of three backup fuels, but typically rely on a liquid fuel, typically a No. 2 diesel oil, while operating with water injection for emission control of NO_x.

By the late 1990’s environmental pressure pushed for the development of a turbine design that would minimize NO_x emissions without the use of water injection. The top-down regulatory effort pushed all the OEMs to implement design programs to develop the Dry Low NO_x (DLN) or Dry Low Emission (DLE) burner design (Davis, 1989). In these designs natural gas is premixed with air prior to ignition in the combustor (the extra air fulfilling the role of the water in terms of temperature control). The result was a substantial NO_x reduction. While natural gas could be mixed with compressor air and not ignite, the physics of combustion did not allow premixing with fuel oil (safely), primarily because fuel oil has a much lower ignition temperature.

[4] Here fuel quality refers to the combustible material in the fuel, not necessarily the contaminants, like metals or ash.

With hundreds of millions invested on DLN/DLE designs (over 30 years), NO_x emission from modern gas turbines were reduced from the 100-300 ppm range down to 5-10 ppm levels (GTA, 2021). This was a major engineering achievement, but such low emission capability came with a significant limitation in fuel flexibility. Since 2000, virtually 95% of all gas turbines put into operation in the United States were single-fueled natural gas DLN machines. NO_x emissions were down, but so was fuel flexibility.

System-wide redundancy could be improved by reintroducing some measure of fuel flexibility, with a backup fuel (such as Jet-A, Diesel No. 2, or propane). How might that work in ERCOT's unique "energy only" market? Figure 2 provides some idea of the number of operating hours needed to recover an investment to increase fuel flexibility in a 1,000 MW gas turbine (combined cycle). Assuming market prices reach \$3,000/MWh, a \$60 million investment to expand fuel flexibility for the operator could potentially be recovered in 20 hours of operation. Implementation in ERCOT would have dampened market prices downward from \$9,000/MWh, where the cost recovery period is as short as a day or two.

As indicative in Figure 2, the wide swings observed in an energy only market could absorb a substantial retrofit cost to improve fuel flexibility. The most likely fuel candidate for this task would be either a No. 2 fuel oil (or Jet A). It may be possible to expand that capability using novel technologies that safely allow premixing of fuels that would typically auto-ignite or cause detonation. *(R. Joklik, 2011)*

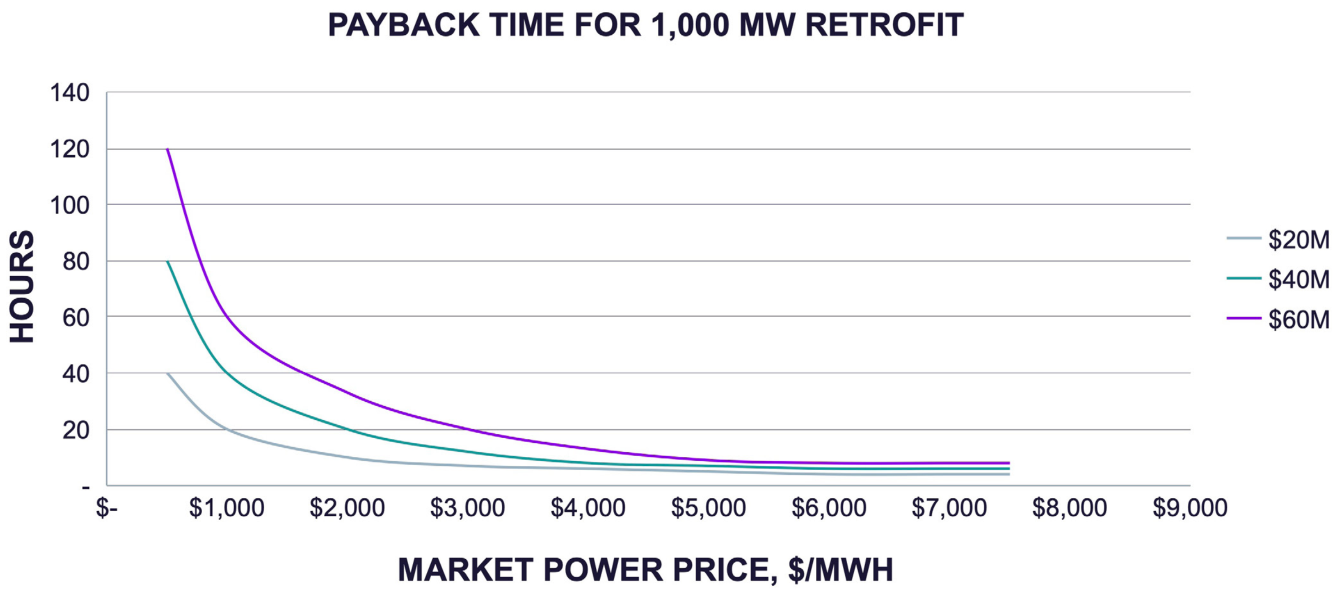


Figure 2 Estimated payback time for backup capability in an "Energy Only" market.

2.2 Gas Supply Security

In normal circumstances, Texas has a significant gas surplus relative to demand (shown in Figure 3). Data from the Texas Railroad Commission and the US Energy Information Agency as well as Siemens Energy Power Generation modeling indicate that daily average net production (net of outflows) is typically near double the daily demand. With daily deliverable storage volumes taken into account, Texas has access to over three times the daily average consumption.

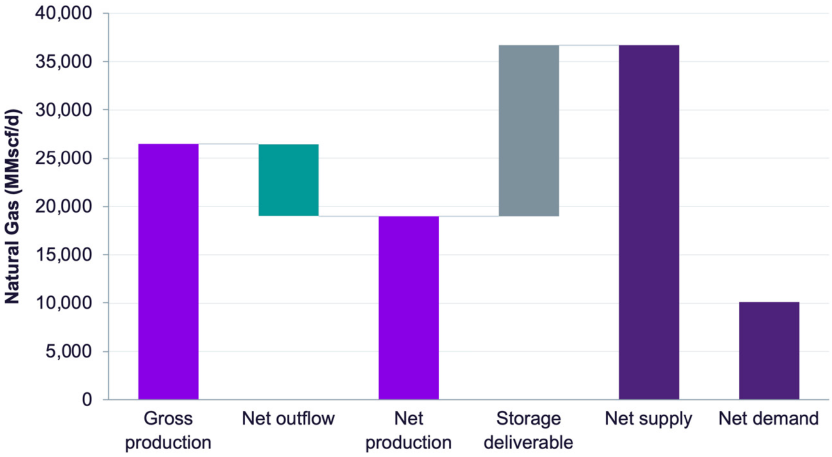


Figure 3 Texas natural gas supply and demand balance (Baseline).

This typical surplus should not be misunderstood. During Winter Storm Uri, Texas' natural gas infrastructure experienced substantial curtailments, both in production and transportation. While these curtailments ultimately did not lead to gas shortages[5], our analysis indicates that for a storm in 2024, assuming winterization efforts succeed and all natural gas power plants are available when called upon to provide load, produced gas in the state will not be sufficient to supply the demand from power plants, households, and other consumers.

A fully functioning gas storage network is the key to a secure fuel supply for Texas during demand shocks, especially as production declines.

This is true for our modeling of extreme heat and hurricane scenarios as well, where local curtailments of production and storage deliveries can be offset by storage gas and then made up once supply and demand return to their normal surplus condition (results are highlighted in Figure 4 with additional details in Appendix G).

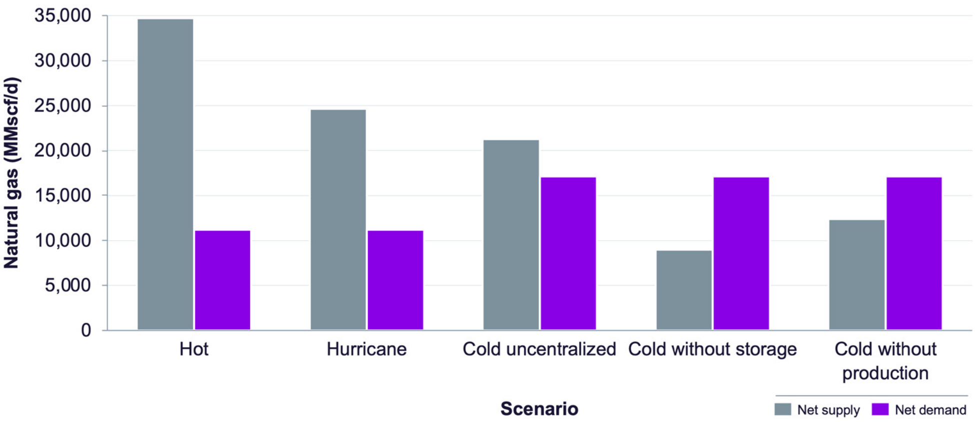


Figure 4 Texas natural gas supplies and demand balance (Modeling Scenarios).

[5] Gas demand had decreased because a significant number of gas fueled power stations were offline. This led to an unexpected, and short-lived gas surplus.

To increase the confidence in the gas supply during periods of peak demand, incentives could be a tool to achieve the following:

1. Expanded daily deliverable volumes from existing gas storage sites.

2. New gas storage sites in South Texas, which has no major gas storage and delivery infrastructure.

3. Cold weather resilience measures for major interstate and intrastate pipelines, gas plants, and gas gathering systems.

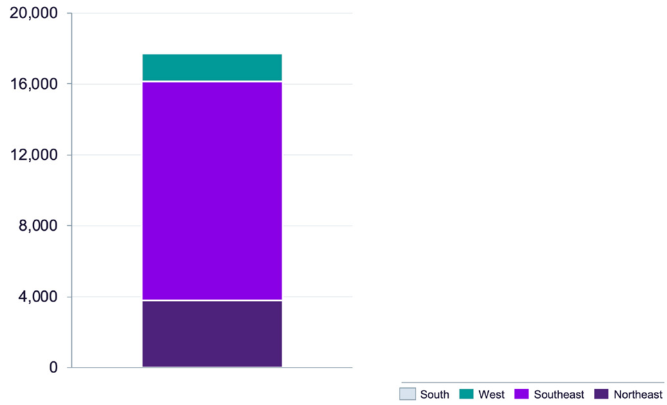


Figure 6 Natural gas storage deliverables (MMscf/d)

In total, Texas has over 600 billion cubic feet of working gas stored in 39 sites inside the state or nearby in the Permian and Haynesville plays. From these sites, approximately 17.7 billion cubic feet of gas can be extracted and delivered daily. See Figure 5 and Figure 6. These sites are located primarily in more populated regions of the state (Northeast and Southeast).

Securing delivery from 39 storage sites that will not change with production decline is a far more expedient avenue toward security of supply than thousands of well sites.

As noted previously, “produced gas”, or raw natural gas, is comprised of a mix of hydrocarbons, water, and carbon dioxide. Each of these elements exhibits different phase behavior, and the mix of these elements differs from well to well and reservoir to reservoir. With the thousands of sites producing gas in the state, and the many hundreds more being added each year, such improvements would be costly relative to the benefit they would deliver.

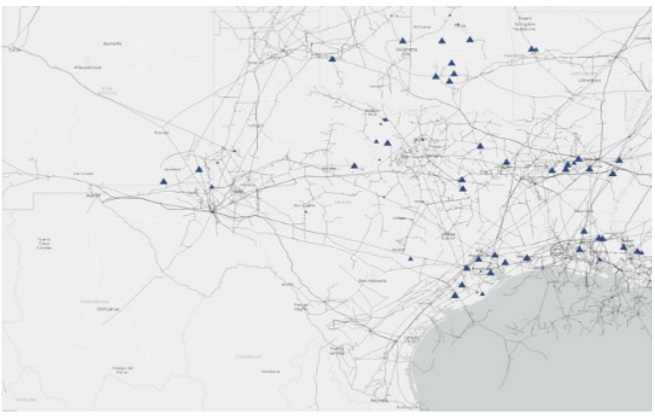


Figure 5 Gas storage and infrastructure in Texas and surrounding regions.

Our modeling also indicated that while intrastate pipelines are critical to balancing supply and demand across the state in higher-than-average demand conditions, the state has sufficient excess capacity. Our scenarios included the shutdown of one or more pipelines in the zones that were also subject to supply and demand shocks to drive conservatism into the modeling effort. For all scenarios in which there was adequate supply via production and/or storage, the state’s pipeline network was able to transport gas between regions to satisfy demand. It’s expected that local outages could lead to curtailments at a local level. **Therefore, adequately maintaining the laterals that deliver storage gas into the major interstate and intrastate pipelines is critical. These laterals also should be exempted from load shedding to ensure that they don’t render available stored gas undeliverable.**

2.3 Major Grid Disturbances in the United States

Information on grid disturbances is available from the U.S. Department of Energy. A detailed breakdown of system failures, and their causes, is documented in Appendix D.

Comparing NERC regions, the total number of customers impacted within the ERCOT (TRE) region is significant, but overall, it ranks fourth in scale of events to occur in the continental U.S. power grid. Reliability First Corporation (RFC) reported a maximum of 8 million customers impacted in a single month over the ten-year period. These figures shown in Table 1 were determined by finding the maximum number of affected customers for the month in question across a decade of events. (717,206 customers affected in 2011 was the maximum for that ten-year interval). For ERCOT (TRE) the maximum customer impact for any February was the most recent one in 2021.

2.4 Power Supply Options

The United States is comprised of numerous power grids, similar in that they use essentially the same generation equipment technology, design methods, and system operations. They rely on natural gas fired turbines, coal fired boilers, nuclear power, solar, and wind to supply electrical power to customers.

The basic technology choices for producing electricity can be grouped into two broad categories:

1. Dispatchable power generation
   a. Gas fired turbines, coal plants, nuclear plants, reciprocating engines, steam turbines, etc.

2. Non Dispatchable power generation.
   a. Wind turbines.

   b. Solar power (essentially photovoltaic).

Table 1 Peak number of customers impacted by weather related events between 2011 and 2021.

Maximum Weather Impact Customers (2011-2021)							
	WECC	TRE	NPCC	FRCC	MRO	SERC	RFC
January	1,170,997	188,000	80,000	-	-	1,355,716	717,206
February	383,841	4,905,248	229,247	-	503,107	826,404	1,203,739
March	270,332	274,414	826,313	137,000	-	498,181	2,619,203
April	318,719	629,967	408,476	49,999	-	2,519,719	389,591
May	2,800,426	655,269	436,049	-	-	538,073	647,388
June	4,200,000	1,218,017	135,442	-	593,000	1,188,526	8,071,881
July	82,000	333,208	158,131	-	250,000	440,540	1,625,066
August	2,924,268	2,782,636	2,556,179	440,000	610,000	2,192,914	3,701,163
September	1,666,500	65,000	155,000	5,397,555	-	1,882,683	564,400
October	1,874,210	752,037	2,720,891	1,365,000	-	1,851,199	3,393,050
November	571,000	-	178,408	-	-	628,448	841,146
December	433,970	881,000	290,231	-	34,500	380,872	238,304

In addition, there are some smaller, and unusual, examples that cross boundaries between these two (e.g., compressed air energy storage, or CAES).

The non-dispatchable power components can improve their market exposure by including energy storage into the energy delivery equation. Inclusion of large sets of batteries (of various technical designs) has the potential to allow the wind-solar suppliers to fulfill roles they have yet to achieve (e.g., peak shaving). However, to date there is a much greater supply of non-dispatchable capacity when compared to the ability to store this energy for use during periods of peak demand. This creates a unique situation that forces the dispatchable power systems to cycle in a method that coincides with the availability of the non-dispatchable elements. Batteries with up to 4 hours storage capacity is one way to supplement potential supply shortfall at critical times.

3. Root Cause Analysis

No single event or action was wholly responsible for what transpired in February 2021. As we report in Appendix D, weather has been a persistent factor in the ability to deliver energy in nearly every grid subsystem in the United States. It has been the primary factor that resulted in millions of customers disconnected from the grid. Smaller, less extensive outages are persistent in every grid, but typically are not documented by DOE. Several smaller failures are attributable to animal intrusion.

3.1 ERCOT's Recent Weather History

ERCOT has seen weather events previously that had impacted the energy supply system. In 2011 a cold weather snap dropped temperatures below freezing. The cold weather affected users in the southwestern U.S., even forcing a workforce reduction at several national labs in New Mexico. As shown in the following figures, temperature drops were not as severe as encountered a decade later. But the weather factors did result in reports suggesting improvements would be needed.

A consultant retained to examine the ERCOT problems during the winter of 2011 provided recommendations, many of which seem to still be appropriate to current operations. A brief note on the analysis state:

> **"When actual conditions breached the design parameters, some owners and operators were not properly equipped to effectively manage the impacts to maintain their units in operating condition."**
>
> (Quanta, 2012)

Similar events were to unfold a decade later. A comparison of weather conditions between 2011 and 2021 reveals that conditions were even worse a decade later. Temperatures were colder than in 2011, with substantial precipitation. As will be highlighted later, substantial increases of non-dispatchable wind capacity had been added over the same time period.

Compounding the problems of cold weather, the measured wind speed data in the area 200 miles west (near Abilene), had also declined precipitously for a period, reducing wind potential generation output to near zero (see Figure 8).

The observation of the low wind speed in this region is important because there is a significant supply of wind turbine capacity within a 150-mile radius. Presumably, low wind speeds and low temperatures could have been spread over an even broader area.

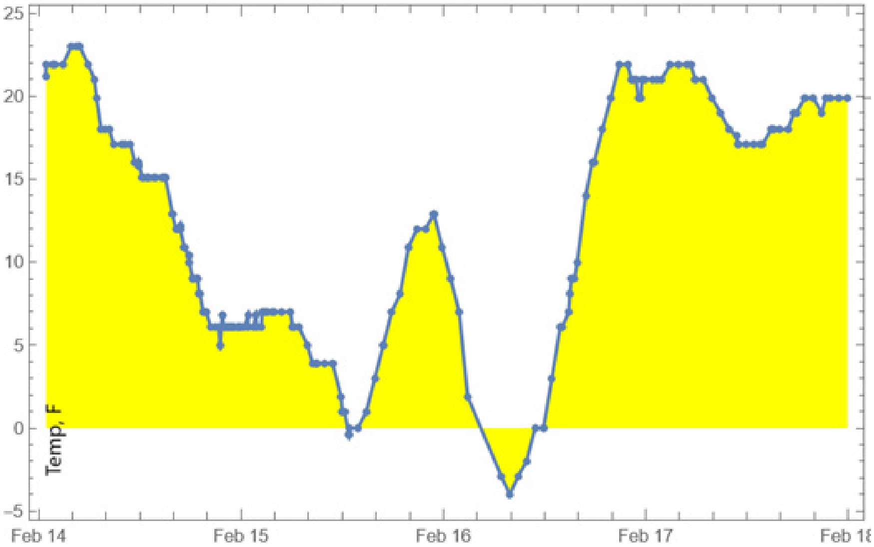


Figure 7 Temperature data in Abilene, TX, center of significant installed wind capacity.

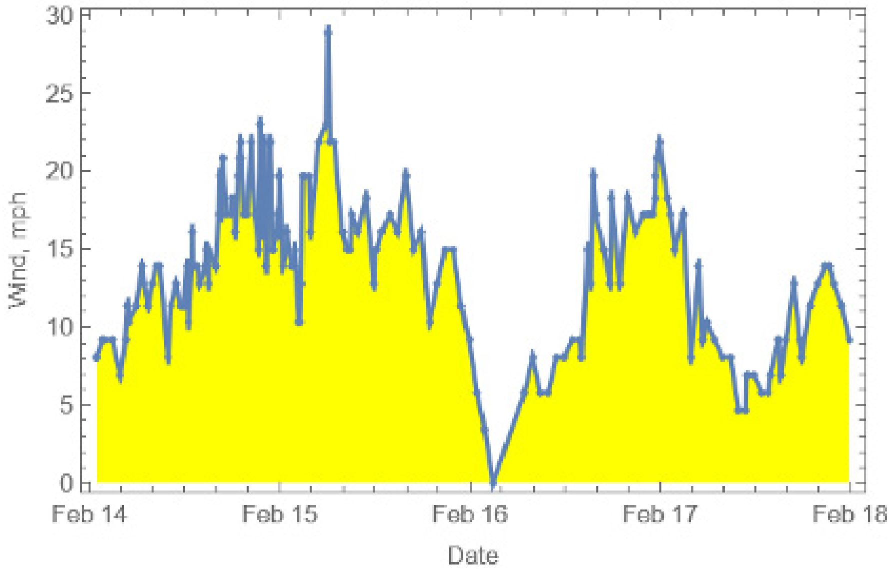


Figure 8 Wind speed data, Abilene, TX. Low wind speeds on the 16th of February are near coincident with low temperatures, suggesting both factors contributed to system problems.

3.2 ERCOT's Isolation

The isolation of the Texas power grid shields system operations from federal oversight by the FERC, as well as protecting the system from faults beyond its boundaries. Faults within its boundaries must still be overcome by resources only within ERCOT. As power generation technologies evolved in the mid twentieth century, it became evident that the ability to build, own, and operate power generation was not limited to the domain of large, regulated utilities. Private equity entered the market, and it was then possible to raise substantial amounts of capital for power generation without reliance on customers. By 2000, the state had deregulated its power system, separating the power generation, transmission, distribution, and power marketing operations. While individual elements of the chain were separated, there was only limited ability to move energy into or out of ERCOT. Isolation from other markets could limit ERCOT's response to an extreme event.

3.3 Electricity Resource Base: Gas and Wind Supply

ERCOT, and Texas in general, has a vast resource base, including wind, natural gas, oil, and nuclear. Since 1999 there was significant growth in the natural gas fired generation. This expansion took place almost immediately after deregulation and continued as demand grew.

3.4 Natural Gas

With such a large installed base of gas generation, a reliable supply of natural gas, even under the worse conditions, is an absolute requisite. Yet data from EIA reveal that gas production dropped markedly during the winter storm. The sharp drop off is obvious in Figure 9.

In the previous storm of 2011, gas production fell substantially due to a "freeze off" at the production sites. Wellheads in Texas are generally not freeze protected, leaving them exposed to the elements and at risk to the impact of temperature extremes.

Also, gas processing facilities dependent upon grid power were able to obtain reduced power costs by participating in a load shedding program where the operators receive preferential power pricing as part of a commitment to disconnect during periods of high-power demand. Such programs are not unusual for industrial users, but this unique customer involvement had the ability to create a dangerous feedback loop on the system accelerating the loss of gas supply which reduces power.

As shown in further details in Appendix G, Siemens Energy modeled the natural gas infrastructure of Texas zonally, incorporating production, storage, transportation, and consumption at a regional level to simulate the macroscopic dynamics of the gas system.

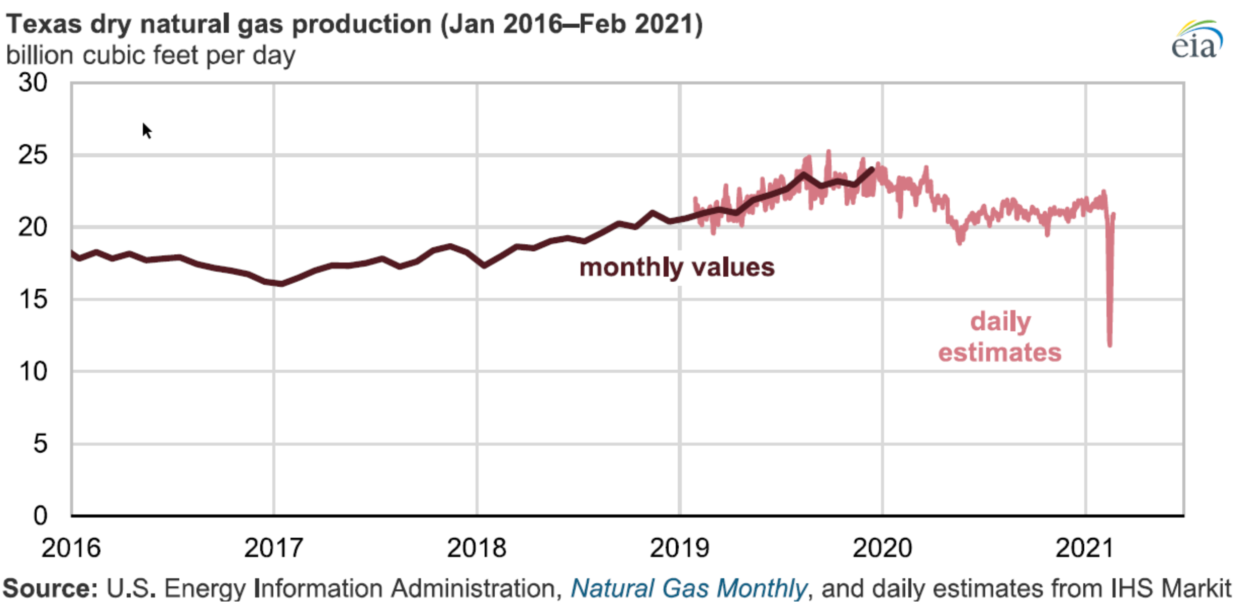


Figure 9 Texas gas production: the winter storm appeared to strongly impact output. (EIA/DOE, 2021)

The intent of this modeling was not to derive market prices for gas or identify local disruptions; rather, it was to:

• Understand the macroscopic flow dynamics for the state's gas infrastructure

• Identify where supply shortages were likely to occur in each of the scenarios

• Determine high-level recommendations for improvements to the state's gas infrastructure, which would inevitably require further evaluation and site-specific action on the part of the owners

The natural gas infrastructure was modeled as four regions: Northeast, Southeast, West, and South. For definition of these regions, see Appendix G. Production, storage and consumption data for each region were interconnected digitally via a model of the state's gas pipeline infrastructure. We validated this model by simulating the response of gas infrastructure during Winter Storm Uri. Our analysis of the event confirmed the Texas Railroad Commission's assertion that gas supply exceeded gas demand, but that had gas from storage not been available and had all of the natural gas fired power plants been winterized, demand would have exceeded supply. This was further confirmed in modeling of a future winter storm similar to Uri. The main conclusion generated from this analysis is that as natural gas production in Texas declines over the next decade, gas storage will become an increasingly important aspect of the state's security of supply during crises. These sites should be maintained to prevent inoperability, and the state should consider incentivizing expansion of daily deliverable volumes of gas storage as population grows and total daily natural gas production declines.

3.5 Gas Quality

On interstate pipelines, gas quality is constantly reported; the information is available online, although typically not easily. Gas quality is critical to gas performance in the pipeline, especially where condensation may occur. The pipelines are designed for the flow of natural gas, not natural gas liquids combined with gases (although there are some pipelines designed specifically for gas liquids and higher molecular weight gases).

Figure 10 provides insight into how changes in the ambient conditions can interact with pipeline operations. In this example, at warmer ambient conditions, no condensation of liquids takes place through a valve in the line (ΔP=700 psi). But as temperatures drop, the volume of liquids that begin to form downstream of the valve increase. To avoid excess condensation, upstream suppliers may reduce the quantity of gas moving through their pipe networks.

Propagation of gas quality to the key regulatory and oversight boards would benefit their ability to understand how the intrastate pipeline system might respond to changing environmental conditions. It may also be effective in developing strategies to counter the impact of ambient conditions on pipeline operations.

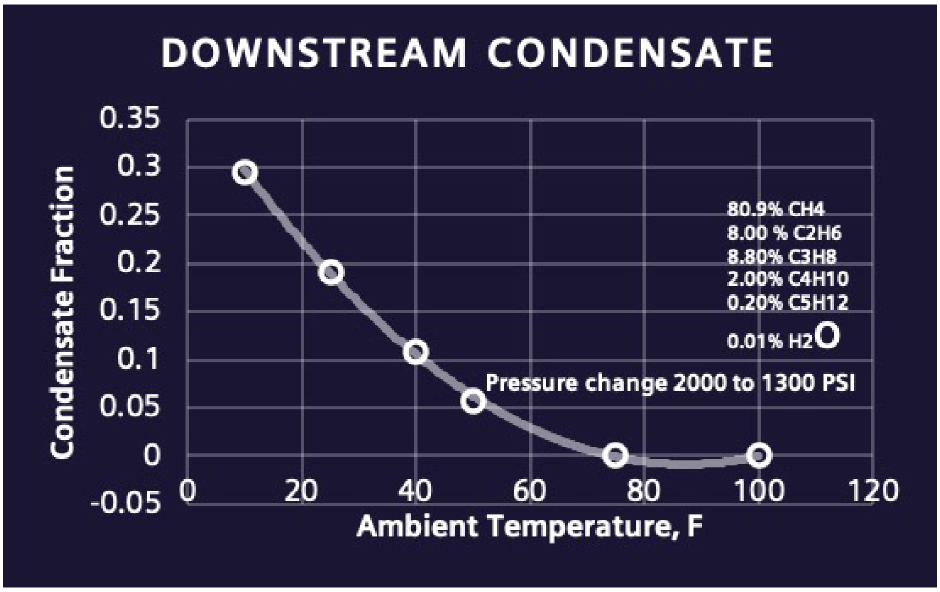


Figure 10 Effect of ambient temperature drop and condensate formation in gas field.

3.6 Wind Resources

Preliminary statements were quickly offered that renewable generation from wind (or the lack of it) played a significant role in generation losses. Specifically, icing of turbine blades was called out. An examination of the meteorological data suggests that a lack of wind may have also been a significant factor. The location of many of the wind resources is depicted in Figure 11, just west (and northwest) of the major urban loads. ERCOT generation data reveal a drop in the wind generation. Wind data in the Abilene area also show a noticeable drop in wind speed, which would also reduce wind power generation.

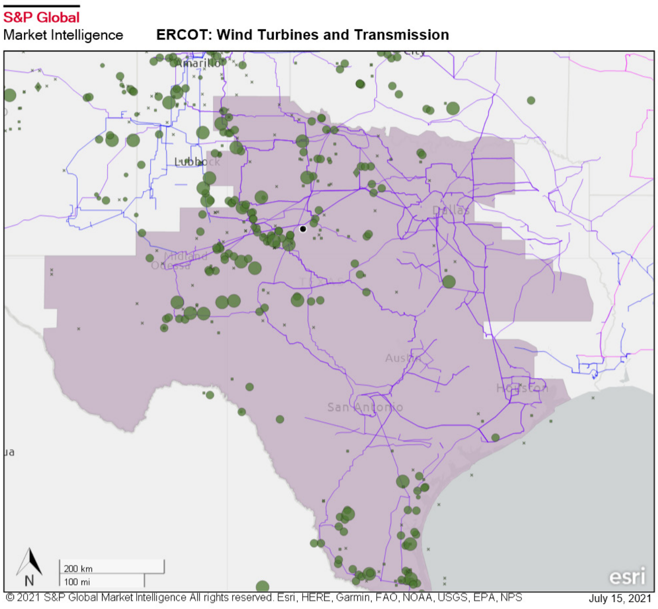


Figure 11 Wind turbine locations in ERCOT and surrounding regions.

By the winter of 2021, ERCOT (Texas) added substantial new wind assets to the power mix, growing from about 9,000 MW of wind in 2011 to over 30,000 MW of capacity in 2021. In addition to the significant growth of the renewable fleet within ERCOT, it was accompanied by the retirement of nearly 12,725 MW of other power sources (with reported service life average of approximately 35 years at time of retirement.).

A significant shift to renewables is quite evident in Figure 12 (renewables classified as non-dispatchable). What role, if any, this substantial supply shift implies is not fully understood. But clearly there was substantial supply of non-dispatchable renewables, this was also coupled with minimal growth in any energy storage capability.

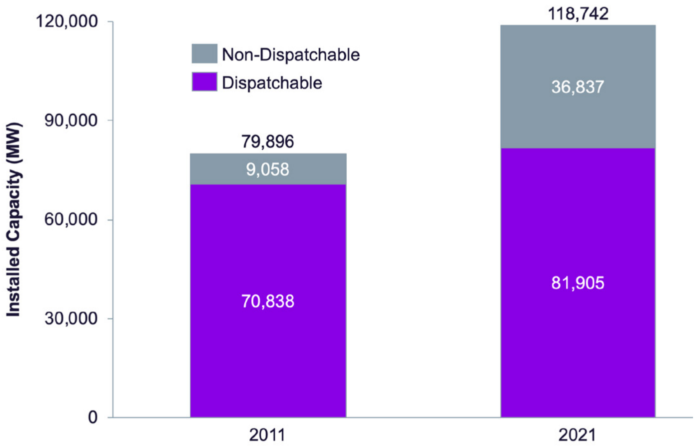


Figure 12 ERCOT installed capacity 2011 to 2021.

3.7 Generation Modeling

To better understand the ERCOT system, Siemens Energy conducted a series of modeling studies (see Appendix E) to see how the system might perform under given reasonable accurate forecasts (e.g., new capacity installations) and combining that with estimated impacts of extreme weather.

This analysis is forward looking to 2024 since the composition of power generating capacity in ERCOT is likely to be different than it is today: more renewables, less coal and natural gas. The 2024 forecast assumed the continued growth of the renewables, with the following additions:

Solar 20 GW

Wind 4 GW

Storage 3 GW

In Figure 13 two cases are shown. The top case is the base case where no extreme events are taking place. The bottom one shows what happens if we constrain the various generation equipment due to extreme weather.

In the bottom case, we have constrained coal and gas on a medium level, wind on a high level and solar on a low level and see that there will be a shortfall potential if the former "status quo" were to be maintained.

Given the expected demand growth and the fact that the new installed capacity is mainly non-dispatchable power plants (solar and wind), we could experience a supply-demand mismatch during extreme weather conditions (one is noted in the simulation results below).

New storage growth is not expected to be enough to cover for these extreme events. The three cases considered were cold weather, hot weather, and storms (hurricanes). In the cold weather scenario, there is a reasonable expectation of a supply-demand mismatch if equipment is not properly winterized to support a lack of wind generation. This is fundamentally based on the loss of gas supply, inoperability of gas power plants and minimal output of solar and wind installations.

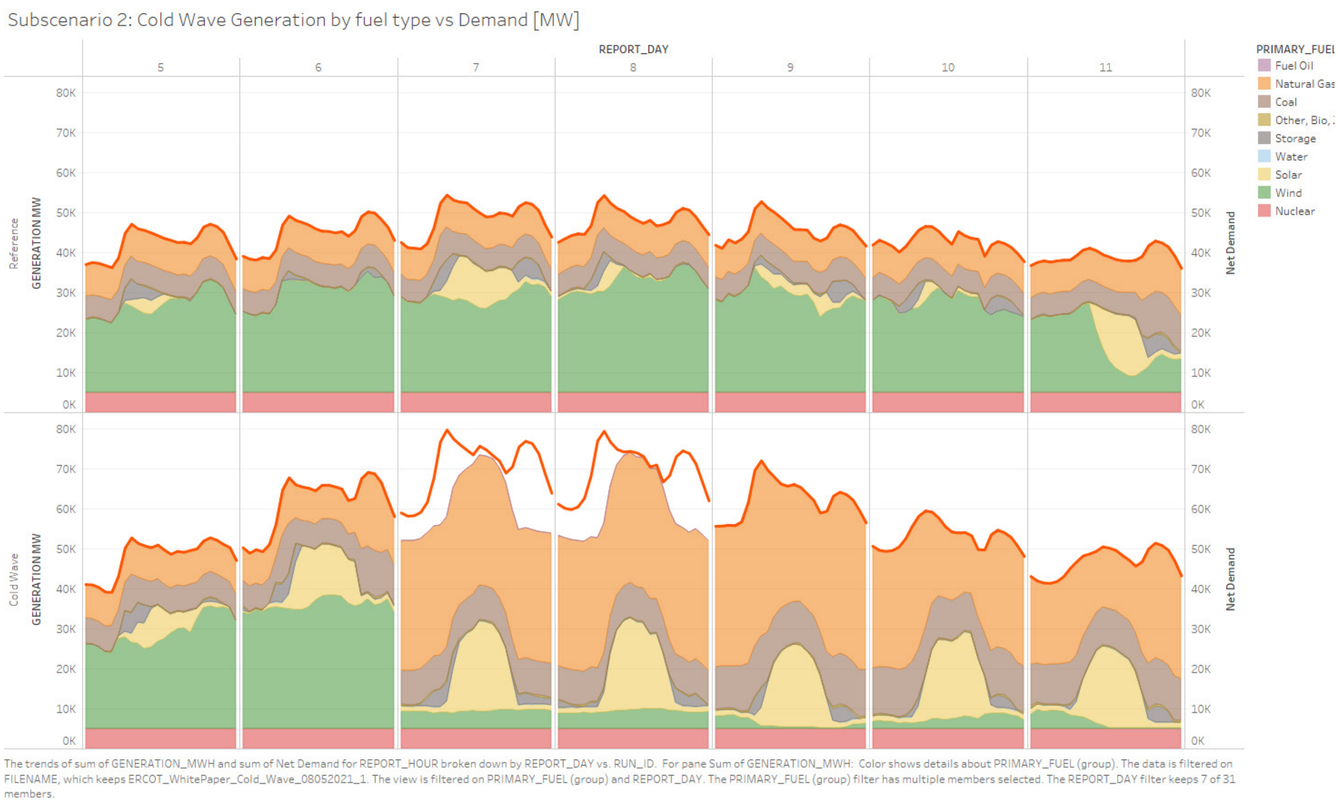


Figure 13 Cold wave generation by fuel type. Demand is shown by the red line.

3.8 Transmission and Distribution

Weather related power interruptions have most frequently disrupted the Transmission and Distribution networks. Nearly all the components are above ground and exposed to the elements. There are good options to explore to enhance system reliability as we outlined in section 1.3 with products like FACTs, SVC Plus, synchronous condensers, UPFC Plus, MVDC Plus and Pretact Grid resilience. Some options identified in other technical reports are:

• The use of pole-mounted reclosers with adjustable reclosing time intervals are a good option for lines with many customers or heavily vegetated areas since they reduce the number of temporary faults that could cause a long-term outage *(Richard, 2018)*.

• Underground placement of key transmission and distribution elements to minimize potential influence of spurious events (e.g., tree limbs, small animal intrusion, etc.).

• Adaptation of novel techniques such as the incorporation of National Weather Service (NWS) doppler radar mapped over existing networks. *(M. Yue, 2017) (Baroud, 2019)*.

There is substantial utility experience in addressing system wide power outages. Depending upon the scale of the problem, most enterprises coordinate with resources beyond their nominal customer base. However, this is typically for manpower and equipment, not necessarily the importation of power.

Recommendations to improve delivery have included system hardening, and the use of new or more advanced methods of identifying and resolving failures *(Richard, 2018)*. However, system-wide reinforcement has its limits, as was demonstrated in Hurricane Ida, where nearly all transmission towers that were "hardened" for post-Katrina events were severed.

Still, improvements are continually being made as our understanding of the power of these extreme weather events becomes more evident. Most recently, Duquesne Light is experimenting with deployment of new sensors to implement "dynamic line ratings". These would allow transmission operators near real time access to information to assess line performance affected by ambient temperature or line sag *(Hale, 2021)*.

4. Recommendations

ERCOT is a well characterized real time energy market. The primary sources of supply are known, information on transmission and load is readily available, and the customer base is well established. But knowledge of these elements was not sufficient to prevent a near-collapse of the system in February 2021.

Every independent systems operator faces challenges of severe weather. Data from DOE reveal that millions of customers across the United States are affected by severe weather and its impact on energy supply. At a high level, some key recommendations include:

1) **Auditing and Inspection.** Routine inspections of critical elements within the three infrastructure systems. These would include on-the-ground inspections to verify equipment preparedness with the OEM's guidelines (See appendix F).

2) **Review of overall system response to simulated extreme events.** This would include periodic modeling of the system to identify weak points in the configuration, beginning with the source, quantity, and location of the energy, to the final distribution.

3) **Ranking of key generation facilities** to include their capabilities of responding to extreme events.

4.1 Resiliency

What has become a term of art in the industry of infrastructure is the phrase resiliency. It suggests system robustness, the ability to respond to stress and quickly return to a stable operating platform.

4.2 Resiliency Strategy

Where oversight is lacking, develop a robust, flexible resilience strategy that integrates stakeholder perspectives[6]. An effective resilience strategy, based on insights from in-depth risk analysis, can prove challenging to develop, design, and execute within an ever-changing, uncertain environment complicated by a range of stakeholder perceptions and priorities. One approach, flexible adaptation pathways can help build robust plans that acknowledge the unknowns and help manage complexity.

[6] In Texas, the recently passed law allows the Governor-appointed commission to examine these types of relationships.

4.3 Resiliency Successes in ERCOT

Overlooked in the challenge of handling a system wide disturbance (or attack) is what might happen on the microscale. For example, HEB supermarkets installed backup generators in several of their stores prior to the arrival of Hurricane Harvey. While much of the Houston area remained in the dark, HEB stores continued to operate using reciprocating engines to run generators. In fact, the stores played a key role in the recovery when emergency response teams used the stores as staging areas. As it turned out in this case, the resiliency of the underground grid of natural gas distribution was significantly better than the above ground electrical distribution network[7].

Of course, small businesses are not the only ones to recognize the benefits of on-site generation. Homeowners, hospitals, and financial institutions have often employed backup generation to fill the gap when the conventional power grid fails. Increased use of backup and emergency generation suggests that consumers do not see the existing infrastructure as resilient as the operators.

4.4 Weatherization and Freeze Protection

In general, weather factors have been the bulk of the source of major disturbances reported on the grid system. In Texas, the recent episodes of cold temperature excursions suggest that cold weather protection of the entire system, as well as individual components, is required. For power generation, freeze protection is a well-established engineering practice.

Most equipment manufacturers provide engineering details related to plant design for robust cold-weather operation. *(J. Brushwood, S. Knott, S. Brown, G. Dizkowski, 1995), (O. Price, R. Royds, A. Bast, F. Shoemaker, B. Edwards, 1999)*. While these requirements are often made available to the EPC and the owner, there is no guarantee that the engineering requirements established by OEM's are fully implemented.

Some actions detailed in Appendix F include:

1) Cold weather (or freeze) protection of assets, including air dryers to remove moisture that can freeze in the plants control air systems.

2) Freeze protection within the gas turbine enclosure, including insulation and heat tracing.

3) Heated steam turbine enclosures for fast start.

4) Heat tracing and insulation of all water or steam filled piping.

[7] "Backup generation booms as electric reliability is rattled". Houston Chronicle. March 02, 2021.

4.5 Energy Storage Solutions

Energy storage is widely used as a solution to shore up the increased demand for electrical power. As already noted, both pumped storage and batteries are deployed for just such a purpose. However, the energy supplied within the fuel itself is a de facto energy storage system. One liter of liquid fuel contains as much energy as 10 kWh. Texas already has massive reserves of energy storage found in both liquid hydrocarbons and natural gas. However, it was the delivery of this gas either from production fields or the storage fields that proved to be the bottleneck.

Some end users already make use of backup generation in the event of a widespread system interruption. Hospitals, with continued operation considered critical, typically have backup generation with minimum fuel storage requirements of 96 hours (NFPA, 2019). For a hospital, and comparably sized facilities, the backup fuel of choice is typically No. 2 heating oil. But even 96 hours would have strained end users who thought they had sufficient fuel resources on hand. An alternative solution would be to make certain that the backup generation can operate on any fuel available.

In Texas, much of the natural gas production is in the sparsely populated western part of the state, in the Permian Basin. Gas pipelines crossing this region move natural gas (and some gas liquids) east towards major power generation users as well as interstate pipelines shipping gas to customers beyond the state borders. However, the largest gas users in power generation are located in the eastern part of the state, as well as gas storage fields. ***Supplementing regional natural gas storage fields with new gas storage fields to be able to amply supply power generators near the major load centers will be prudent.*** (See Figure 14)

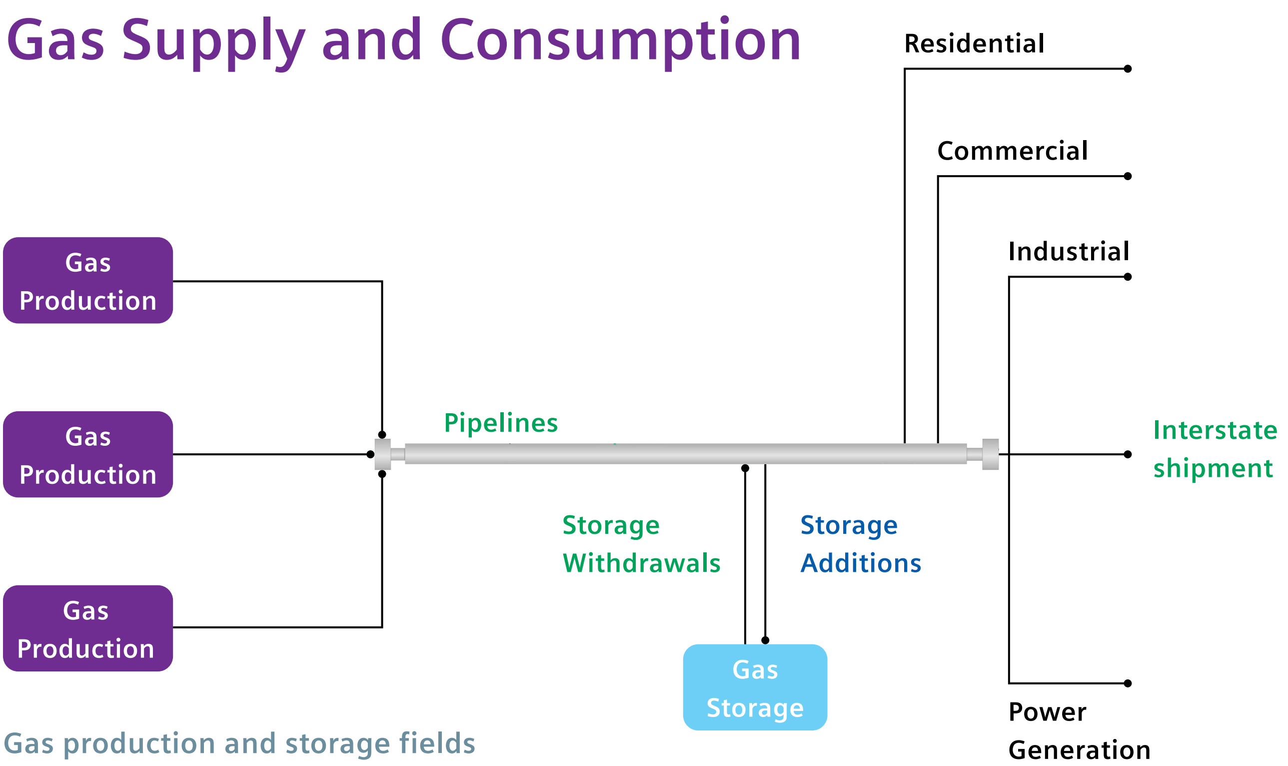


Figure 14 Gas production fields are typically located far from major urban centers. Gas storage fields are often located near both urban centers as well as gas fired generation.

4.6 Gas Supply

Additional measures should be taken to upgrade and digitalize the overall system. Finally the entire system should be considered critical load for the ISO if load shedding is required.

Prioritize Gas Delivery Infrastructure (Gas Gathering Systems, Gas Plants, Pipeline Compressor Stations, and Gas Storage Facilities) in transmission and distribution level load-shedding schemes, particularly in cold weather events.

4.7 Power Generation Supply

NG plants (new ones or upgrading of existing ones) are key to a resilient system that also move us toward decarbonization goals (they are more efficient, hence emit much less CO_2), provided they are weatherized and maintained properly and are paired with a resilient fuel supply base.

Of course, weatherizing wind turbines are another important step toward resiliency and the decarbonization goals for Texas, and elsewhere, as it ensures it is available even during extreme weathers and it is renewable.

For large power generators. Improve the multi-fuel capability for gas turbines. Currently only a handful of combined cycles have dual fuel capability. Adding dual fuel capabilities with couple of weeks of on-site fuel storage via liquid fuels, LNG, LPG can improve resiliency. Of course, hydrogen can also be an option for fuel storage as the gas turbines can also be converted to hydrogen burning mixtures.

Construction of additional natural gas generating plants can also increase backup dispatchable capacity and the system's reserve margin so that it is available when renewable generation is not available.

4.8 Transmission and Distribution

In general, the physical grid (step-up substations, transmission lines, step down substations and distribution lines) more than ever needs updating and digitalizing (simulations of extreme conditions using digital twins, protect against cyber-attacks, enable better forecasting, and risk mitigations) to ensure grid reliability and stability with respect to voltage, frequency, and transients as well as improved efficiency.

Installing synchronous condensers, FACTs devices, SVC Plus, UPFC Plus, MVDC Plus, Pretact Grid resiliency (as explained in Section 1.3), and upgrading the substation equipment not only can help with resiliency, can also help toward decarbonization using SF6-free equipment.

Additional improvements in design include building enough redundancy in general, but against heat, provide additional cooling, reflective coating, sunshades, or indoor installations. For severe flooding and deep snow, elevate equipment (or install barriers) and utilize higher support structures, build special drainage system, or wall system, and seal control rooms.

Even though Hurricane Ida brought down many post-Katrina "hardened" transmission towers, there are ample opportunities remaining for improvement (e.g. replacing wooden poles with concrete).

Despite the above resiliency measures, the power restoration still depends on lots of factors such as which equipment failed, how remote is the site, how quickly the crew can locate the failure, are spare parts available, do new substations need to be built, etc. which then recovery could be from few hours to many months.

5. References

Baroud, J.-Z. Y. (2019). Quantifying Community Resilience Using Hierarchical Bayesian Kernal Methods: A Case Study on Recovery from Power Outages. Risk Analysis, 1-20.

Davis, L. a. (1989). Development of a Dry Low NOx Combustor. ASME Paper No. 89-GT-255.

EIA/DOE. (2021, February 25). Today in Energy. Retrieved from EIA/DOE/Gov: https://www.eia.gov/todayinenergy/detail.php?id=46896

Energy, U. D. (2021, 7 22). Office of Cybersecurity, Energy Security, & Emergency Response. Retrieved from Office of Cybersecurity, Energy Security, & Emergency Response: https://www.oe.netl.doe.gov/oe417.aspx

ERCOT. (2021). Roadmap to Improving Grid Reliability. Dallas: ERCOT.

GTA. (2021, 7). Private communication. Gas Turbine Association. Washington, DC, US.

Hale, Z. (2021, 9 1). Utilities eye grid-enhancing technology incentives amid U.S. infrastructure push. Retrieved from S&P Capital IQ: https://www.capitaliq.spglobal.com/web/client?auth=inherit#news/article?id=66404031&KeyProductLinkType=58&utm_source=MIAlerts&utm_medium=real-time-minewsresearch-newsfeature-energy%20and%20utilities-the%20daily%20dose&utm_campaign=Alert_Email

J. Brushwood, S. Knott, S. Brown, G. Dizkowski. (1995). LS POWER WHITEWATER PLANT FUNCTIONAL REQUIREMENTS FREEZE PROTECTION. Orlando, FL: Westinghouse Internal Report.

M. Yue, T. T. (2017). A Bayesian Approach Based Outage Prediction in Electric Utility Systems Using Radar Measurements. Brookhaven, NY: Brookhaven National Lab, BNL-114128-2017-A.

McKinsey. (2021). Texas Energy Study.

NERC. (2021). Cold Weather Grid Operations Preliminary Findings and Recommendations. NERC.

NFPA. (2019). NFPA 110 Standard for Emergency and Standby Power Systems. National Fire Protection Association.

O. Price, R. Royds, A. Bast, F. Shoemaker, B. Edwards. (1999). 21T0348 AES IRONWOOD PROJECT FREEZE PROTECTION FUNCTIONAL REQUIREMENT. Orlando, FL: Westinghouse.

Quanta. (2012). Report on Extreme Weather Preparedness Best Practices. Austin, TX: Quanta Technology, LLC.

R. Joklik, L. E. (2011). Low Emissions power Generation using Natural Gas Condensates. Proceedings of ASME Turbo Expo 2011, 1-6.

Richard, J. (2018). Grid Hardening and Resiliency. Leidos Engineering.

NERC, (February 2021), Cold Weather Grid Operations Preliminary Findings and Recommendations-09-23-21

Published by

Siemens Energy, Inc.
4400 Alafaya Trail
Orlando, Florida 32826
USA

Authors:
Bruce Rising, Martin Tartibi, Sander Ray, Santos Garza Romero, Marvin Benjamin, Cristina Becle, Chris Ferraro, Allan Skinner, Nathan Zeller, Ricardo Moraes, Sebastian Raue, Timothy Findling, Sergey Kynev, Alexander Rentschler

For more information, please visit our website:
siemens-energy.com

Siemens Energy is one of the world's leading energy technology companies. The company works with its customers and partners on energy systems for the future, thus supporting the transition to a more sustainable world. With its portfolio of products, solutions and services, Siemens Energy covers almost the entire energy value chain – from power generation and transmission to storage. The portfolio includes conventional and renewable energy technology, such as gas and steam turbines, hybrid power plants operated with hydrogen, and power generators and transformers. More than 50 percent of the portfolio has already been decarbonized. A majority stake in the listed company Siemens Gamesa Renewable Energy (SGRE) makes Siemens Energy a global market leader for renewable energies. An estimated one-sixth of the electricity generated world-wide is based on technologies from Siemens Energy. Siemens Energy employs more than 90,000 people worldwide in more than 90 countries and generated revenue of around €27.5 billion in fiscal year 2020.

Appendix A

A Weather Impacts

Hurricanes in the Gulf of Mexico are not uncommon. More than a few have struck the Gulf coast over the years. Two different storms were examined, Hurricane Ike (2008) and Hurricane Harvey (2017). Of the two, Hurricane Ike produced much more high-speed winds on the coastal areas (Hurricane Harvey produced much more significant rainfall). Interestingly, there was minimal impact on the wind velocity in the interior part of the state, suggesting that coastal storms have only modest impact relevant to wind power generation in the interior.

A.1 Weather Impacts

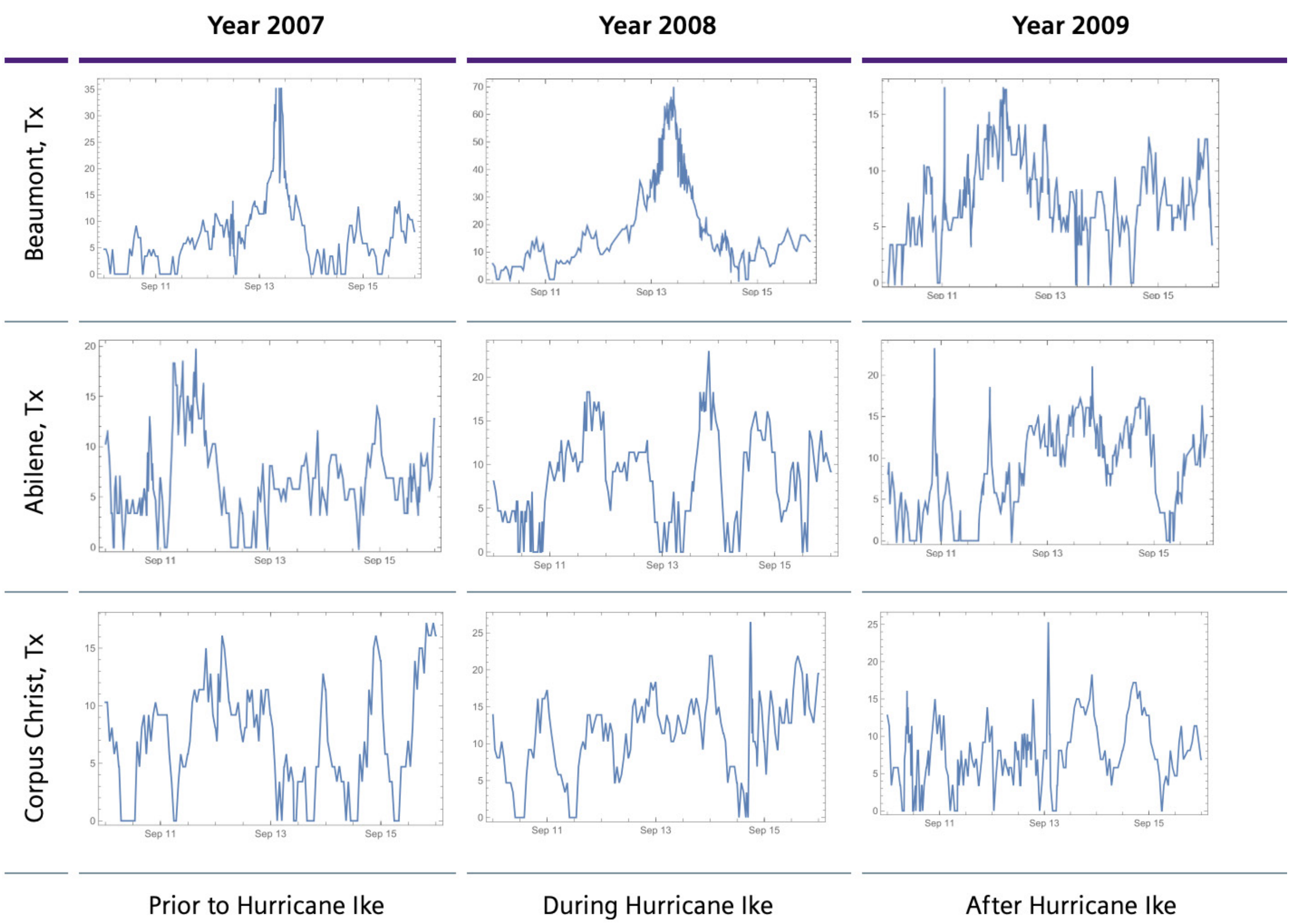
Total installed wind in the state is over 30,000 MW. In the upland interior region of the state, within a 100-mile radius of Abilene, are 11,000 MW of operating wind turbines. This area was impacted by cold weather, its high altitude being one reason. Along the coastal area, just south of Corpus Christi to the border with Mexico, lie another 16,000 MW of installed wind capacity. This group of wind turbines is more likely to be impacted by a hurricane of gulf storm than the interior regions of the state.

Appendix A

A.2 Hurricane Risk

Hurricane Ike made landfall near Galveston, Texas on 13 Sep 2008. Along the coastline measured windspeeds reached over 75 mph. But the wind field was not so broad as to impact wind turbines that might have been placed in operation there. As it turns out, few wind turbines were in place along the coast during this time period, so there would have been minimal, if any, impact on facilities there. However, as the charts show, there were several days of high wind speeds along the coast, which would most likely have forced wind turbines in the area to cease operation.

Table A.1 Wind velocity data three regions, one year before, during and after a major hurricane.[8]



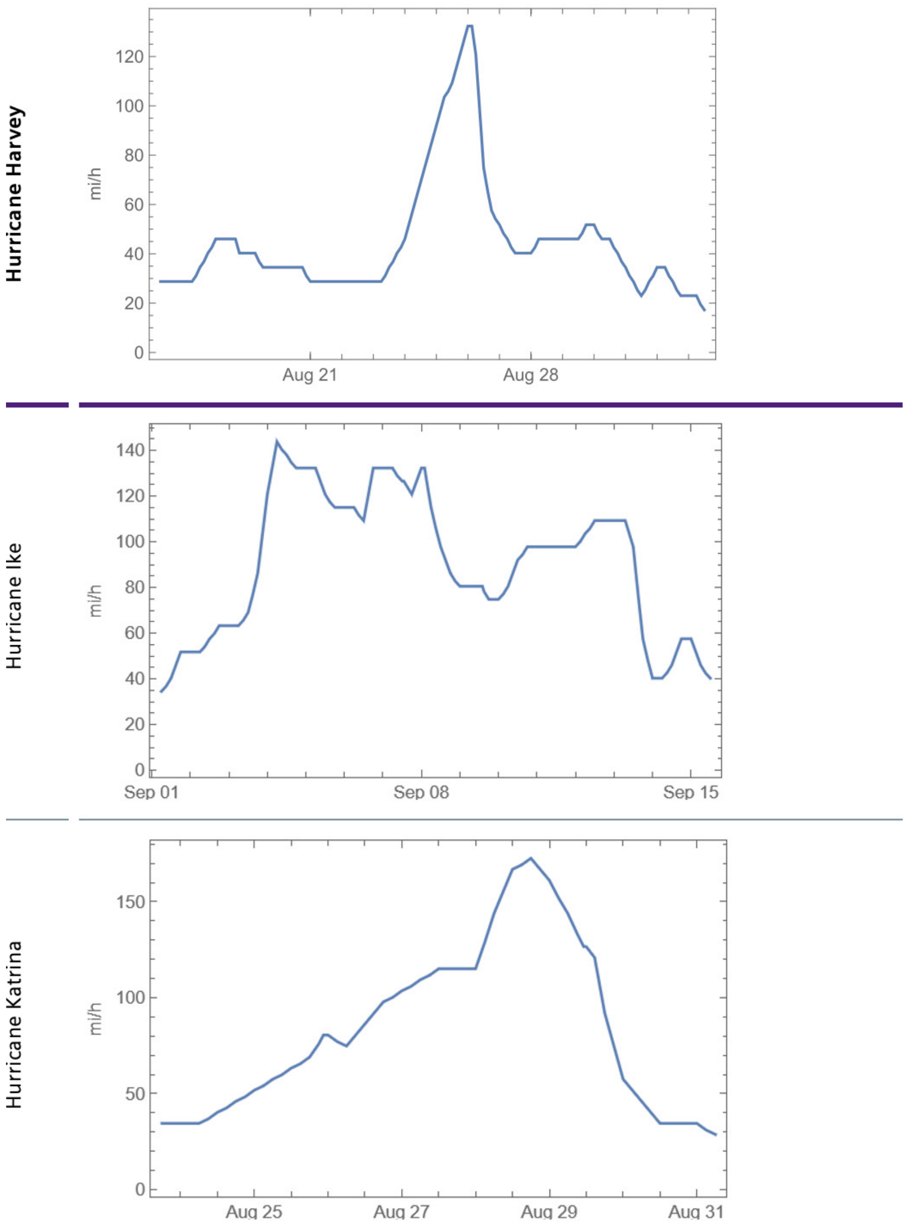
[8] Source: National Weather Service historical data for selected sites.

Appendix A

Note that in the period prior to Hurricane Ike (2007), the wind velocity data look similar to the year the hurricane struck. The obvious difference is that maximum wind speeds during the storm are almost a factor of 2 higher than the prior year, and a factor of 3 higher one year later.

While Harvey did cause extensive damage, primarily through flooding, Hurricane Ike would have been much more devastating because of the long period of high wind speeds. The following figures show the reported wind speed from local weather stations over the critical period of the storm maximum. Wind turbines will nominally "cut-out" at 50 to 75 mph wind speed. Hurricane Ike presented substantially increased risk levels for a period of nearly 14 days compared to either Harvey or Katrina.

Table A.2 Storm comparisons.



Appendix A

Also, along the coast, in Corpus Christi, reported wind speed data did not show the same strong wind characteristics found along the coast near Houston-Beaumont, suggesting that perhaps the impacted wind turbine fleet have a relatively small footprint. In fact, from year to year, wind speed data did not change significantly. The time period when wind data were above turbine cut-out speeds was approximately 6 hours.

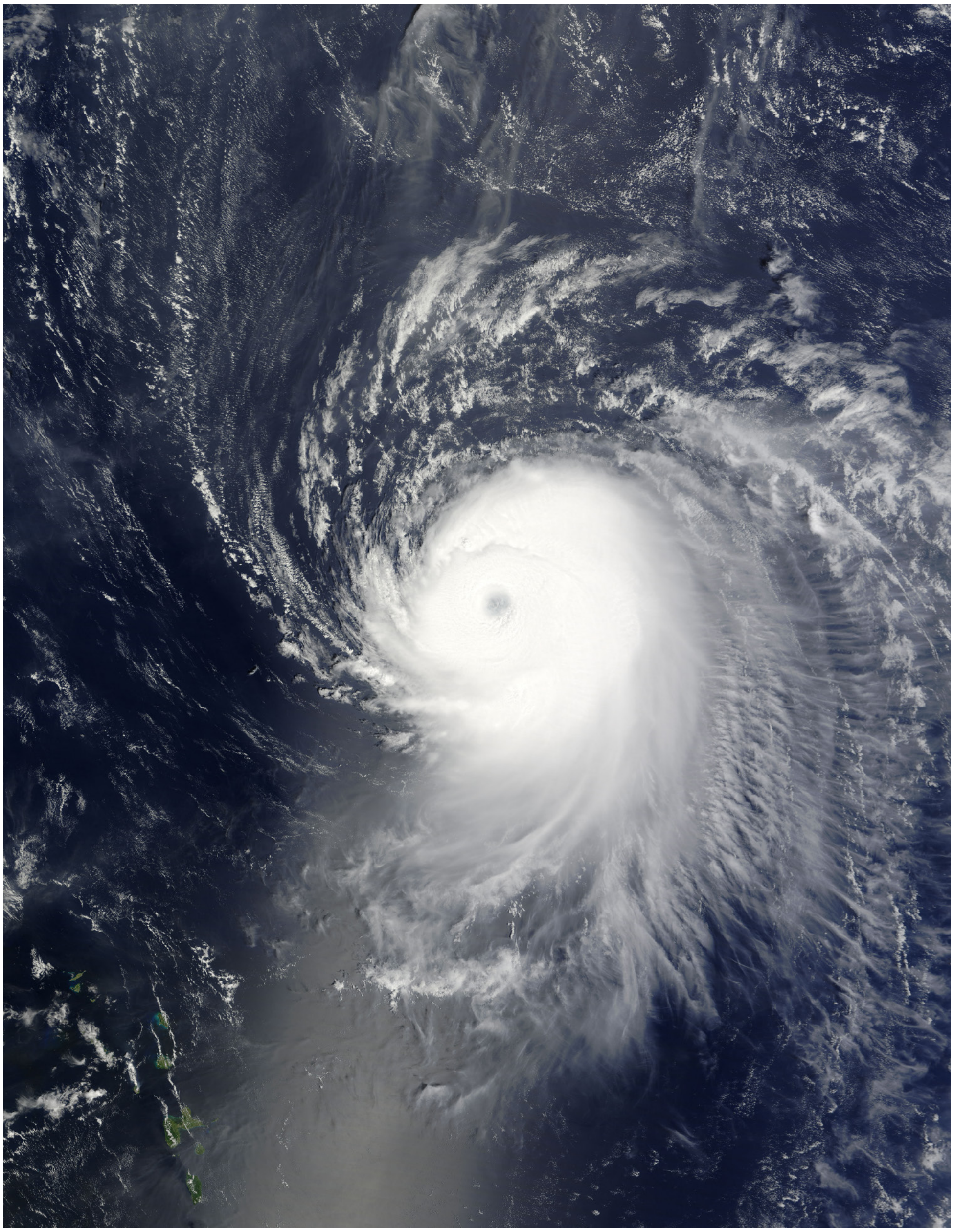


Figure A.1 Hurricane Ike 4 Sep 2008.

Appendix A

Much farther inland, wind speed data near Abilene (an interior region with substantial wind reserves) showed minimal impact related to the storm. In fact, there's little to indicate the presence or evidence of a hurricane from the data. One reason why is the steep incline that the storm would have to overcome to reach the interior regions of the state. It represents a rise from 26 ft to over 2,000 ft. Any wind turbines located on the coastal zone are nearly 2,000 feet below the elevation of those in the interior.

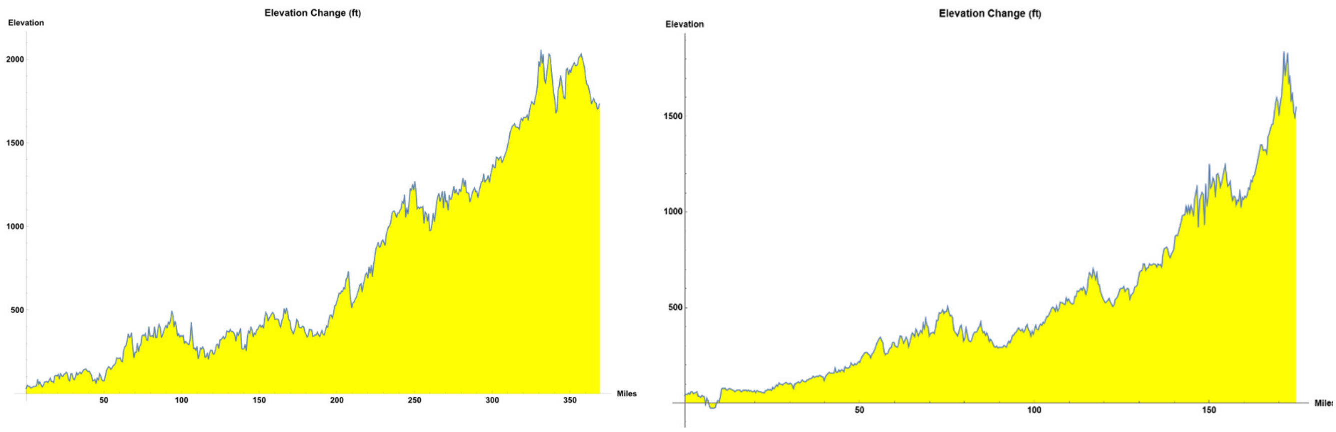


Figure A.2 Elevation changes from Beaumont to Abilene (left) and Corpus Christi to Abilene (Right).

Had the storm struck farther south, and a decade later, the wind impact on power generation (essentially from overspeed) would have been much larger, potentially impacting more than 1/3rd ERCOT's supply.

Appendix A

A.3 Cold Weather

Events in 2021 certainly changed things from previous winters. With a record demand in power, and supply of natural gas limited, ERCOT was hovering on the brink for several days. Yet, a similar temperature excursion occurred nearly a decade ago. This is depicted in the temperature shown in Figure A.3. However, the perfect storm this time was the fact that the ambient conditions were more extreme in February 2021 driving up electricity demand, ERCOT was relying much more on wind due to much larger installed capacity and as Figure A.4 indicates, the wind speeds were quite low during the coldest episode of 2021 and hence not producing much power.

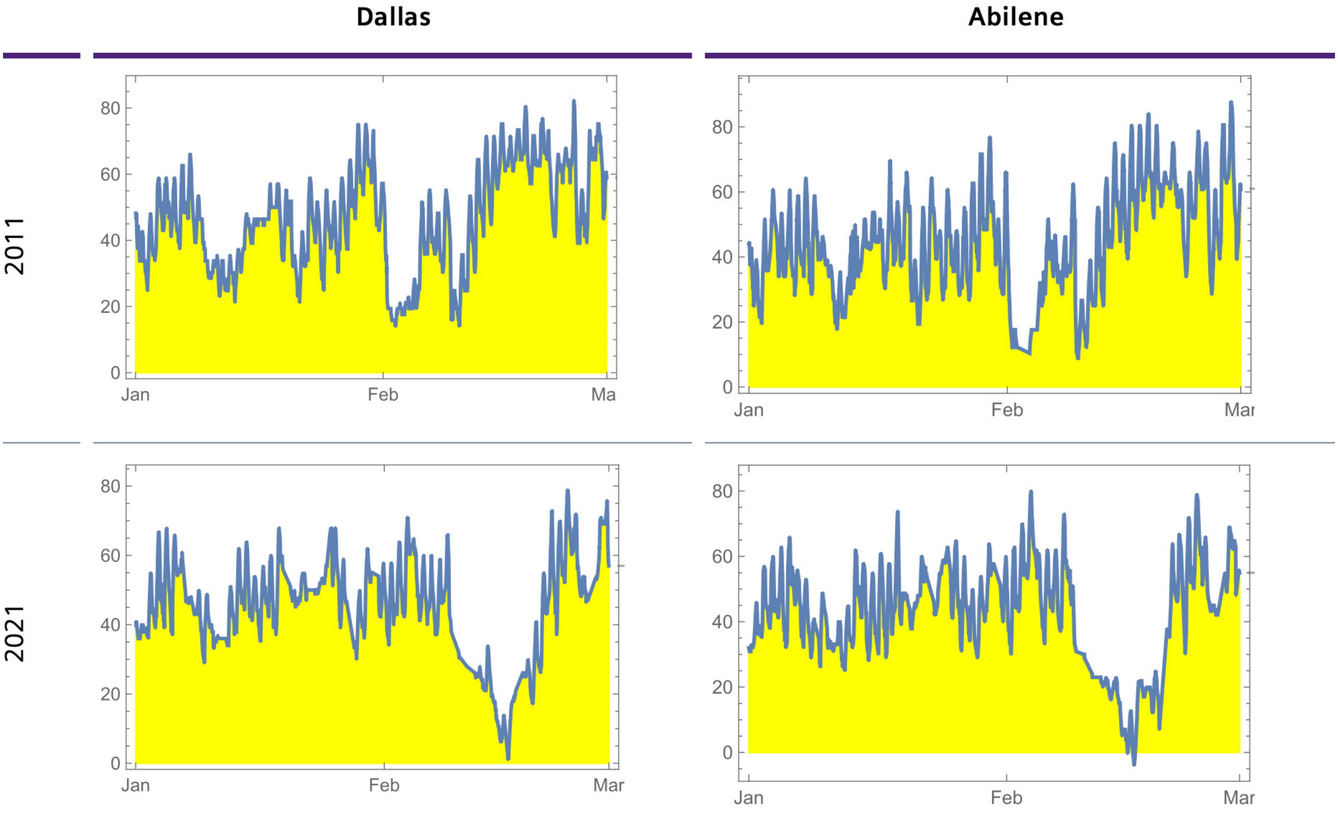


Figure A.3 Temperature data. Within ERCOT, and Texas specifically, unusually cold weather events occurred in both February in 2011 and 2021. Dallas, a major load center, also experienced severe cold weather suggesting that power demands would be above norms. Abilene, which is near the location of a large number of wind turbines experienced somewhat colder weather because of the higher elevation.

Appendix A

While temperatures had dropped to below zero, wind turbine output should have only been minimal for a period of 6-7 hours on the 16th of February 2021, based on reported wind speed data. But low wind speeds are not uncommon during this month, as one can see from 2011 data. However, by 2021, the installed capacity wind capacity increased 200% in the state of Texas. Appropriately winterized equipment should have been able to respond to demand for power in the hours following the temperature minimums.

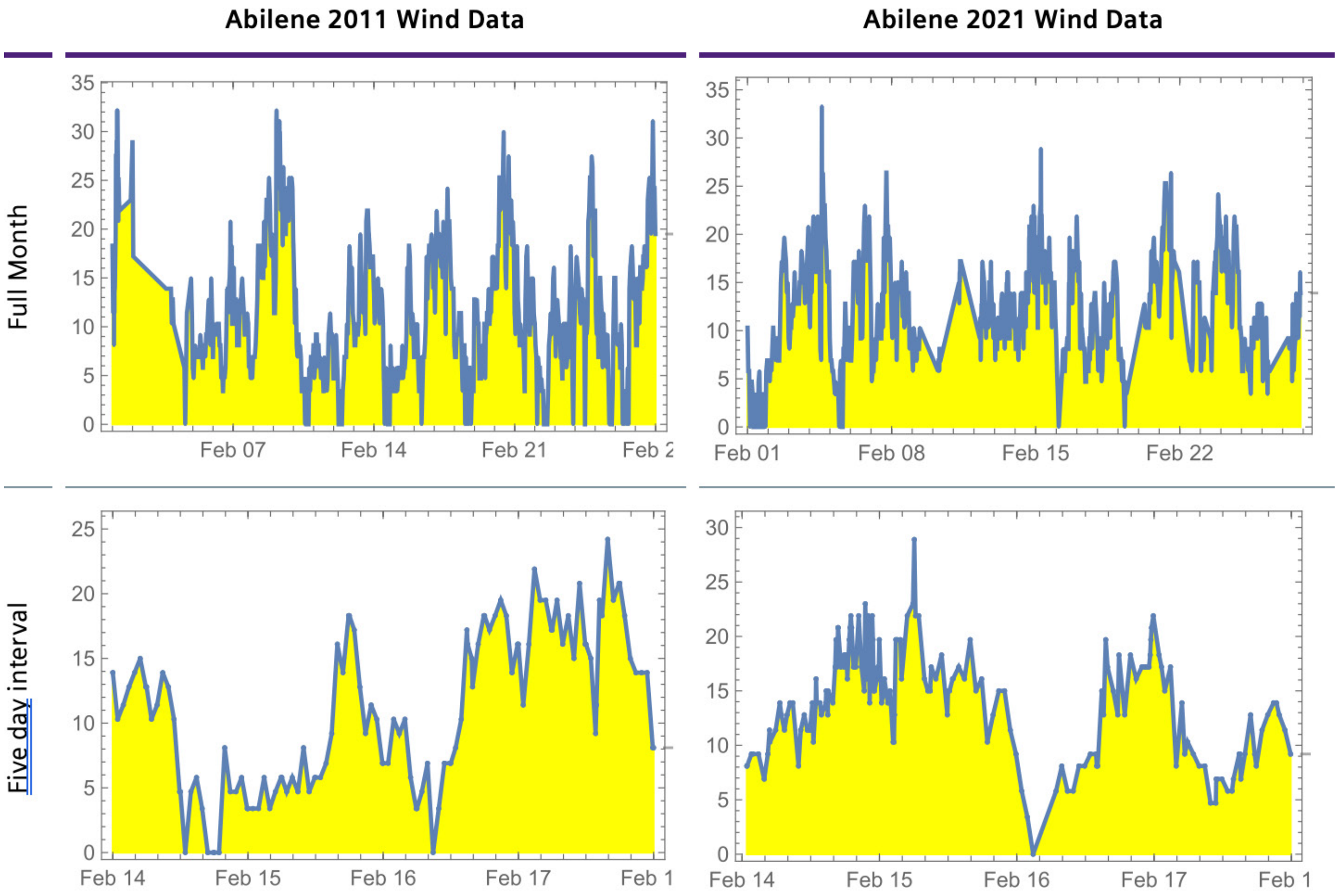


Figure A.4 Wind speed data in Texas interior wind turbine region. Cold weather in 2011 doesn't seem to correlate to the wind data, although there is a good correlation between wind and temperature in 2011. But by 2021 wind capacity had increased by 200%.

Appendix A

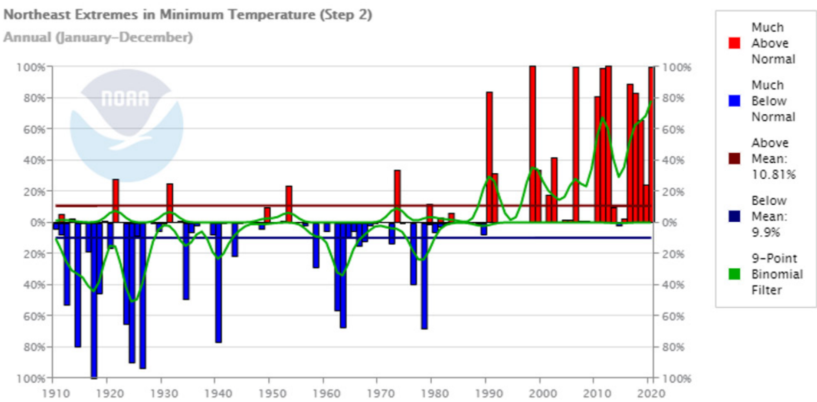
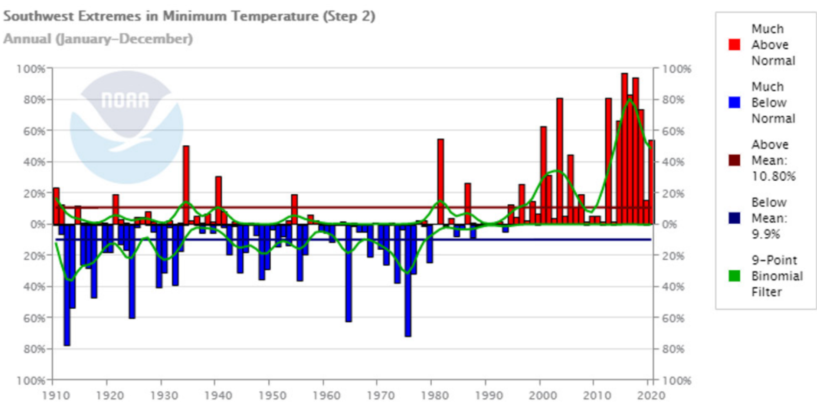
A.4 Extreme Weather

Extreme weather refers to those events that appear to be well beyond the historical norms for meteorological conditions. These might include extreme high temperatures, extreme low temperatures, excessive precipitation, etc. Reviewing historical data compiled by NOAA (National Oceanic and Atmospheric Administration) it suggests that more than a few parts of the United States are encountering extreme weather events.

Graphical data from NOAA suggest that since 2000, parts of the United States have experienced a sharp deviation in temperature norms from what is considered a historical normal. Table A.2 highlights the deviation in the minimum temperatures, Table A.3 the maximum temperatures.

The shift toward more extreme weather appears to have occurred just as the United States began deploying large numbers of gas turbines for power generation. The largest volume of turbines were delivered over a relatively short period from 1999 to 2005.

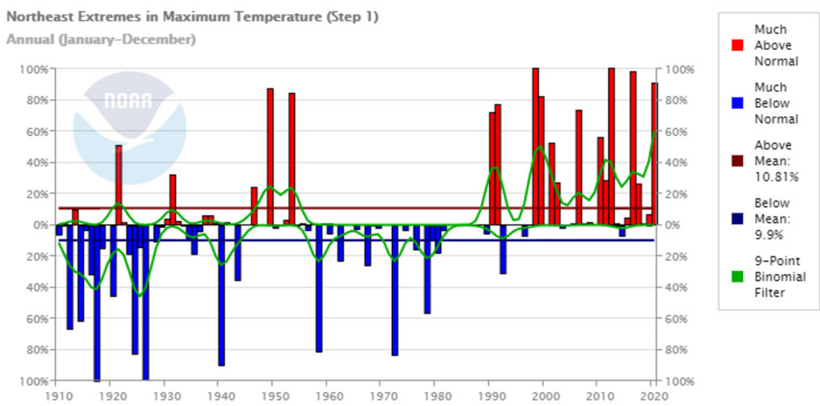
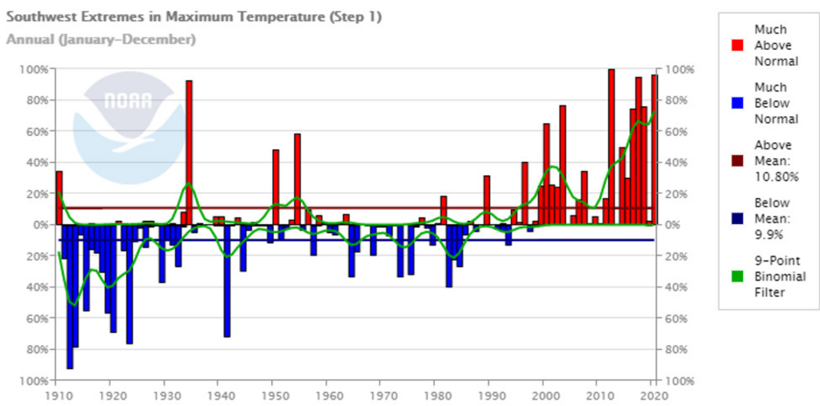
Table A.3 Extreme minimum temperature deviations from historical norms.

Location	Extremes in Minimum Temperatures
Northeast	
Southwest	

Appendix A

The charts show that wide deviations from historical norms were just beginning during this period. One might expect issues of freezing on very cold periods, and reductions in power from facilities relying on cooling water to control steam turbine temperatures. Such occurrences have occurred, but they have not typically impacted a power fleet on a broad scale, at least until the last decade.

Table A.4 Extreme maximum temperature deviations from historical norms.

Location	Extremes in Minimum Temperatures
Northeast	
Southwest	

Appendix A

A.5 Infrastructure

Properly installed and maintained wind turbines are not particularly susceptible to failure to extreme weather events. Even hurricanes that might be expected to cause damage do not affect a wide geographical area with sustained high wind speeds. Wind speed data from coastal areas reveal that a storm coming ashore does not present a uniform sustained wind speed everywhere. Cold weather is another matter, although wind turbines operate in much more extreme environments than noted during recent winter storms. Turbine unavailability (due to low wind speeds) may present more challenges, particularly since the sheer quantity of installed capacity is so large.

Appendix B

B Energy Storage

B.1 Energy Supply: Gas Storage

Substantial amounts of natural gas production is stored underground during the course of the year, to be used during periods of peak gas demand since demand is seasonal and supply remains relatively constant. While the pipeline infrastructure moves enormous amounts of natural gas, it is not large enough to move the quantities of gas that can be required during periods of extreme cold. One possible solution to the gas supply issues within the state is to expand the working gas capacity of the storage facilities. Many of operating facilities are located near the major load centers, including power generation The recommendation is to consider expansion of these facilities in order to store additional gas supply.

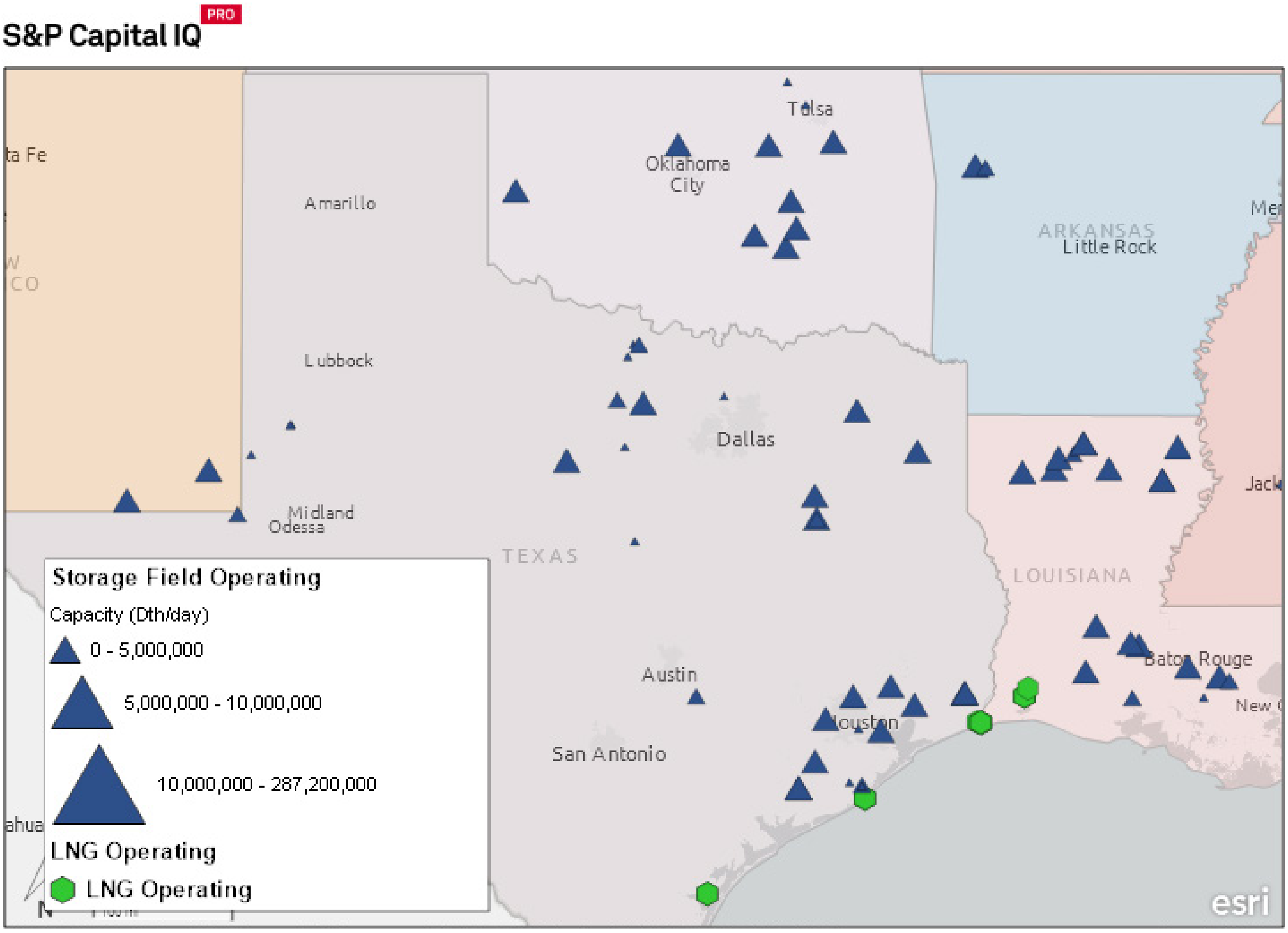


Figure B.1 Gas storage locations and volumes in three key energy supply states.[9]

[9] Source: Gas storage data, installed capacity, and technology type were extracted from SPGlobal database for U.S.

Appendix B

In terms of the total storage volume, Texas can operate at storage levels higher than either Oklahoma or Louisiana. But relative to the installed capacity of gas consuming power generators, Texas exhibits a shortfall of at least a factor of 2. While not all natural gas in storage supply should be expected to be diverted to supply the power generation sector, the larger relative gas storage volumes in Oklahoma and Louisiana might suggest that a gas storage expansion within the state of Texas could potentially alleviate regional gas supply issues when the system is under stress.

Table B.1 Installed power generation and gas storage levels in three key producing states.

	TX	LA	OK
Installed Capacity (MW)	75,041	18,068	15,956
Storage Volume, [Dth/day]	937,173,969	752,729,675	536,964,131
Storage, [mmBtu]	9.37E+14	7.52E+14	5.37E+14
Ratio Storage (Dth)/Capacity (MW)	12,489	41,662	33,652

The following table shows that the bulk of the natural gas consumed within the state supplies a large natural gas fueled turbine fleet, with the largest segment of that being combined cycles.

Table B.2 Gas consumption by technology type within the state (units are Mcf).

	Year 2020	Feb-21	Jan-21	Dec-20
Combined Cycle	2,194,042,619	149,361,089	169,593,829	166,123,100
Gas Turbine	166,114,488	13,401,375	13,552,395	14,034,792
Internal Combustion	4,288,388	646,625	350,812	274,584
Steam Turbine	324,536,771	17,234,741	9,626,371	12,887,039

Appendix B

B.2 Battery Storage

Energy storage is a well-established system of matching excess supply with demand that is non-coincident with the supply. The majority of that energy storage is currently achieved using pumped storage, where excess power is used to pump water into a reservoir at elevation. However, most of the candidate sites for pump storage are already in operation. But new methods of energy storage are being implemented to take advantage of significant abundance of wind and solar resources. Battery storage, or Battery Energy Storage Systems (BESS) are in development and being deployed.

Table B.3 Energy storage within ERCOT and The United States.

	TRE	US
Battery	152.5	1305
Flywheel	5	56
Pumped Storage	0	21876.8

Table B.3 notes that compared to facilities in the U.S. there are few energy-storage options applied in ERCOT. This may change because of continued exposure to weather events, but the rate of change is expected to be slow. The largest quantity of energy storage in the United States is pumped storage, or hydro-electric pumped storage.

Pumped storage takes advantage of candidate sites at elevation where a dam is typically put in place to retain water that is pumped there for short- or long-term storage. Examining the sources of power generation shows that ERCOT appears to have none. But it may not be impossible for pumped storage in Texas. A topographical plot from the Mississippi River (Baton Rouge) to Abilene (a center of wind energy) reveals a gradual rise in elevation. The wind turbines are located at what appears to be the top of a mountain, an ideal location for wind turbine installation.

The distance to move water noted in the figure is less than the current distance for the California State Water Project (CSWP), which covers an equivalent length and elevation.

Appendix B

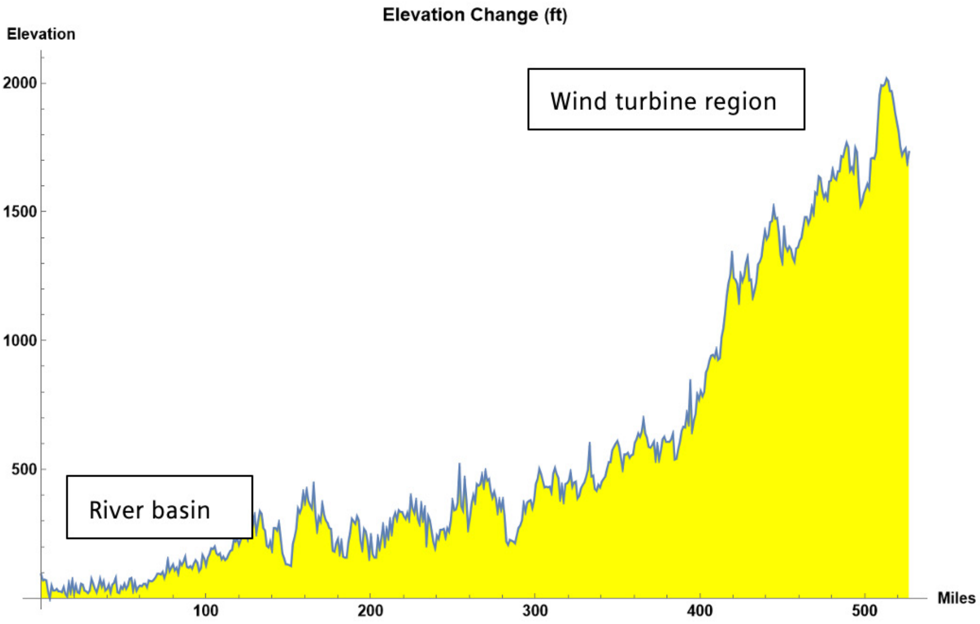
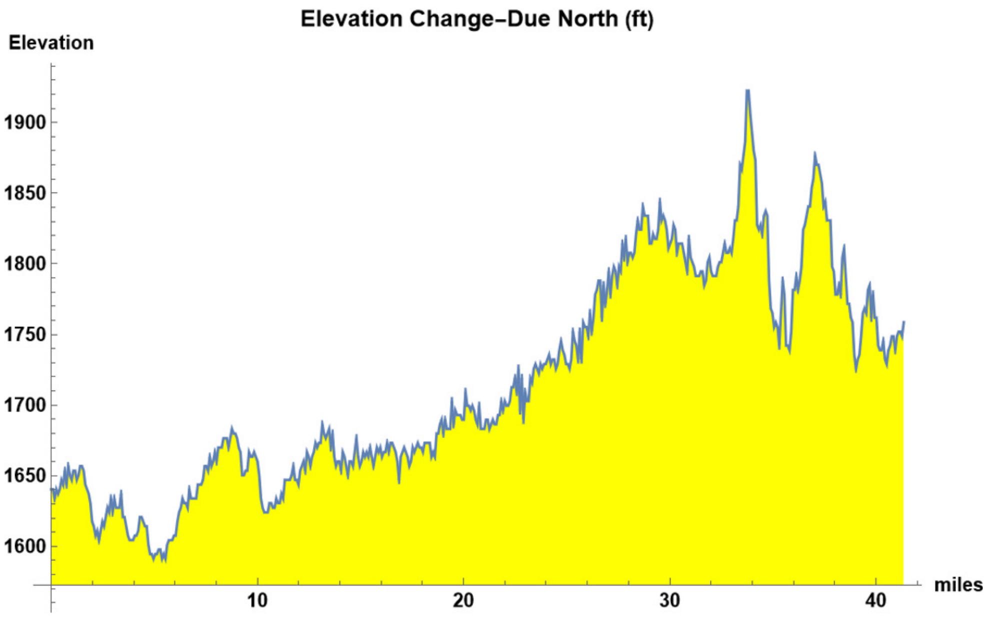


Figure B.2 Elevation change from Mississippi River to Abilene, Tx



A narrower slice of the high-plains area continues to reveal what might be candidates to consider for pumped storage. Additionally, there are already several working storage reservoirs at lower elevations that can serve to receive water from upper elevation storages.

Appendix B

B.3 Interconnections as Energy Storage

ERCOT has followed a path of system independence; it is electrically isolated from the Eastern and Western Interconnections. That isolation has allowed ERCOT, and Texas, to chart a path of energy development substantially insulated from federal oversight. However, ERCOT could connect to other systems (SPP or WECC) without fully interconnecting to them. This would give ERCOT the ability to tap energy supplies beyond ERCOT's boundaries while remaining substantially independent.

The method of connection could be constructed as kind of "electrical system relief valve", accessing capacity in adjacent regions for brief periods to provide temporary support to the general grid. But this may come as some risk to the closest grids. A substantial loss of capacity within ERCOT might risk the stability of any system connecting to it. If the connection were by DC intertie only, ERCOT's regulatory independence might be ensured.

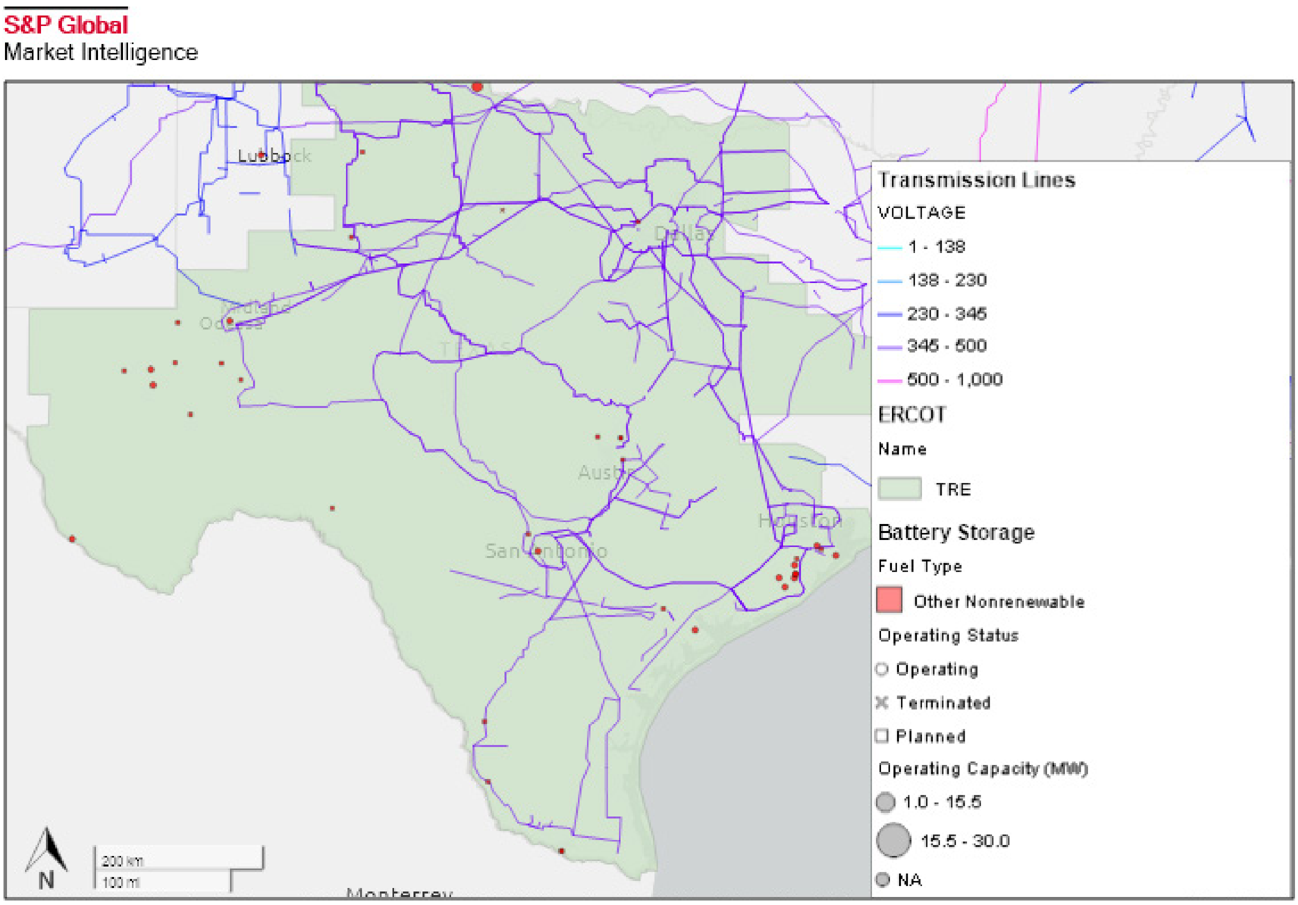


Figure B.3 ERCOT Battery storage distribution and >169 kV transmission

Appendix C

C Ambient Conditions and Weather Impacts

Load data from ERCOT over a period of ten years was examined. The total system load was compared to the temperature on a single point within the region. While the geography is large, a single load center (Dallas-Ft. Worth) was selected as the center point for comparing demand (in MW) against the ambient conditions.

The minimum load data range from 22,000 (in the year 2011) to 27,000 (shown in 2020). These data were obtained across 8760 hours of generation. However, a temperature datapoint was not available for each exact load reading, so the data compare the closest time intervals. Over this period, installed wind capacity increased from 9,000 to 32,000 MW, over 300%. By 2020, the total renewable (and also non-dispatchable) supply now outstrips the total minimum demand. Siemens Energy did not explore the temporal overlap of supply and demand, but there could be reason for concern with a super-abundance on non-dispatchable supply displacing a significant portion of the dispatchable supply.

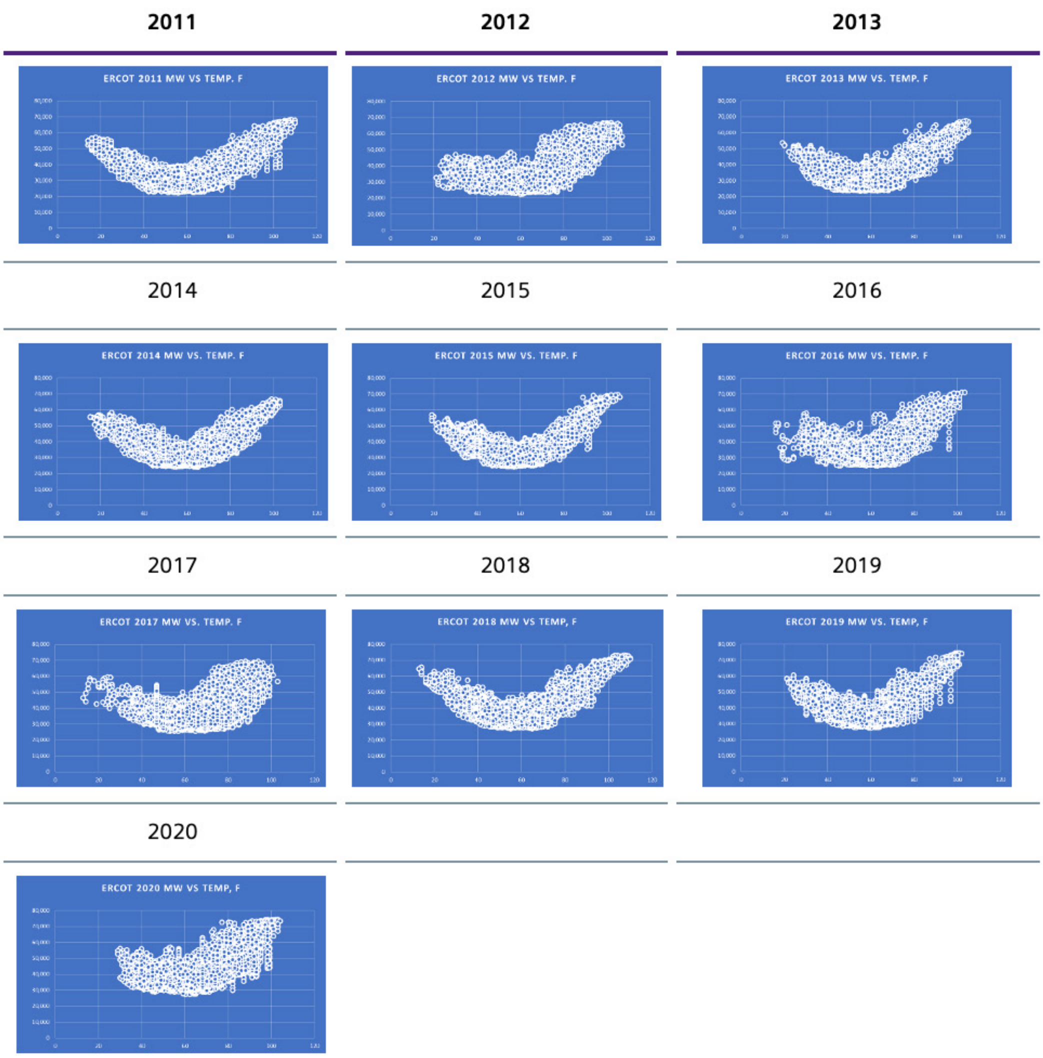


Figure B.4 ERCOT total demand (MW) vs average ambient temperature in the Dallas-Ft. Worth area.[10]

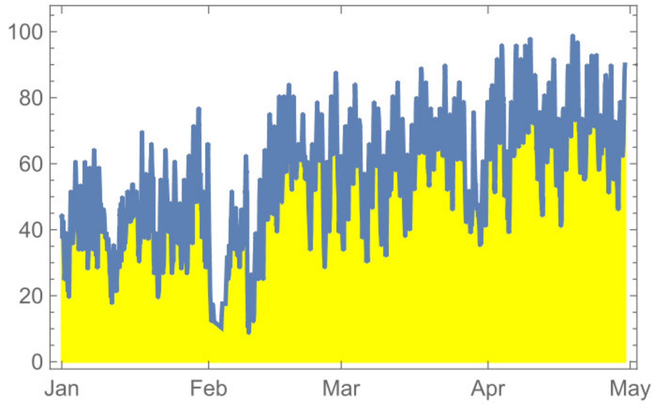
[10] Data extracted from SPGlobal Marketing Intelligence Platform. Annual, hourly load. Temperature data from the National Weather Service for Dallas, TX.

Appendix C

C.1 Cold Temperature Wind Turbine Impact

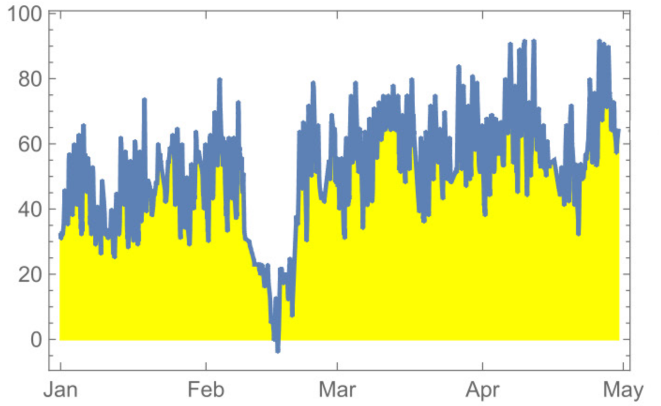
Wind turbines that have not been properly weatherized are at risk of performance degradation either due to mechanical components, or possibly due to the formation of ice on the turbine airfoils.

West Texas, Jan-Apr (2011)



256 Hours below freezing

West Texas, Jan-Apr (2021)

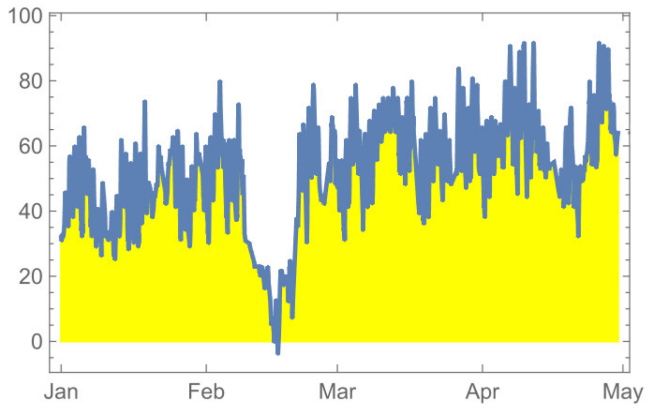


229 Hours below Freezing

C.2 Previous Cold Weather Experience

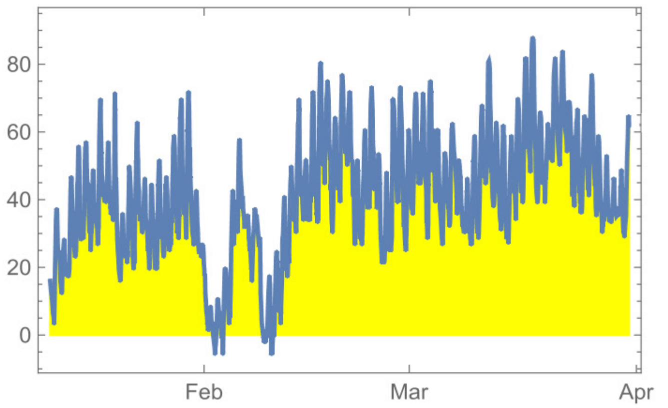
A decade ago, in 2011, the state experienced a deep freeze. In the Panhandle region of Texas, temperatures appeared to reach lows comparable to the 2021 freeze.

2021 (West Texas)



Installed Capacity Approx 10,000 MW 150 mile radius of Abiliene

2011 (Texas Panhandle)



Installed capacity 5,387 MW in 2011.

These weather events are nearly identical. There is clearly ample cold weather experience, based on a comparison of historical weather patterns ten years apart.

Appendix D

D Major Grid Disturbances

D.1 Major Grid Disturbances in the United States

Power grids are a necessity in a successfully functioning modern economy, but despite their near-universal importance, the systems can periodically fail. This has happened in the United States, and it happens frequently in other parts of the world. But as the largest economy, the United States can ill-afford the potential dangers of a widespread system collapse or power outages. Yet, it has happened, and repeatedly. Some regions, like New York, have experienced multiple events. Several of the most memorable disturbances are:

1) 1965 New York system failure.

a. This failure ushered in the era of the small gas turbine Peaker as a fast start power provider to quickly add power to support a grid that had difficulty with black start capability.

2) 1977 New York system failure.

a. This occurred over the summer, where load was high, and supply tight, and a lightning strike at a supply substation. Power from Indian Point was halted, and subsequent transmission lines overloaded. Widespread power outages like 1965 were halted because of implementation of breakers to arrest the voltage collapse and isolate system faults.

3) 1989 Toronto failure.

a. In March 1989 geomagnetic storm occurred as part of severe to extreme solar storms during early to mid-March 1989, the most notable being a geomagnetic storm that struck Earth on March 13. This geomagnetic storm caused a nine-hour outage of Hydro-Québec's electricity transmission system. The onset time was exceptionally rapid. Other historically significant solar storms occurred later in 1989, during a very active period of solar cycle 22.

Table 1 summarizes a decade of system failures across the U.S. In almost every case, weather has been the dominant factor affecting grid stability. The Department of Energy catalogs the most notable disturbances. The nomenclature for the breakdowns is not standardized, so for this summary system failures were grouped into five broad classifications:

1) Weather related: Hurricanes, ice storms, severe weather, tornadoes, etc.

2) Generation, Transmission & Distribution

3) Fuel Supply

a. Inadequate fuel supply, frozen fuel supply, frozen coal stocks.

4) Attack

a. Vandalism, sabotage, cyber-attack, physical attack, etc.

5) Load Shed

Using these methods to catalog the types of failures helps reveal the extent of the impact by each event. The ERCOT winter disturbances (2011 and 2021) are included in this total of 2,338 events.

Appendix D

Table D.1 U.S. grid disturbances 2011 to 2021. Summary of all events during this time[11].

	Weather	Generation, Transmission & Distribution	Fuel Supply	Attack	Load Shed
Customers affected	148,360,823	9,926,745	140,001	344,568	15,872,986
# Of Incidents	1,006	188	78	751	316
MW Affected	455,251	31,150	15,368	23,447	109,276
Maximum single event duration, Hours	337	489	1,812	3,150	95

[11] Data extracted from Electric Disturbance Events (OE-417) Annual Summaries. https://www.oe.netl.doe.gov/OE417_annual_summary.aspx

This is the total for the entire United States. Exclusion of Alaska, Hawaii, and Puerto Rico lowers the affected customer population from 148 million down to 143 million.

These events can also be broken down by their impact on each reliability council region as shown in Table D.2. For example, weather related events with the SERC were responsible for a loss of 282,951 MW of capacity over this period, nearly 8 times the losses in ERCOT (which is listed as Texas Regional Entity, TRE).

Table D.2 Total MW loss related to each category during the period 2011-2021.

	WECC	TRE	NPCC	FRCC	MRO	SERC	RFC
Weather Related	74,091	31,596	9,975	13,626	7,800	282,951	31,371
Generation	21,367	1,483	534	1,613	370	1,489	754
Fuel Related	5,577	1,231	6,947	-	1,613	-	-
Attack	19,030	21	203	55	151	417	3,563
Load Shed	69,921	5,553	551	330	1,839	16,623	7,969

Appendix D

Weather related disturbances appear to reach a maximum of around 5 million customers in any given region as shown in Figure D.1. In comparison to other NERC council regions, the impacted customer base in ERCOT is comparable.

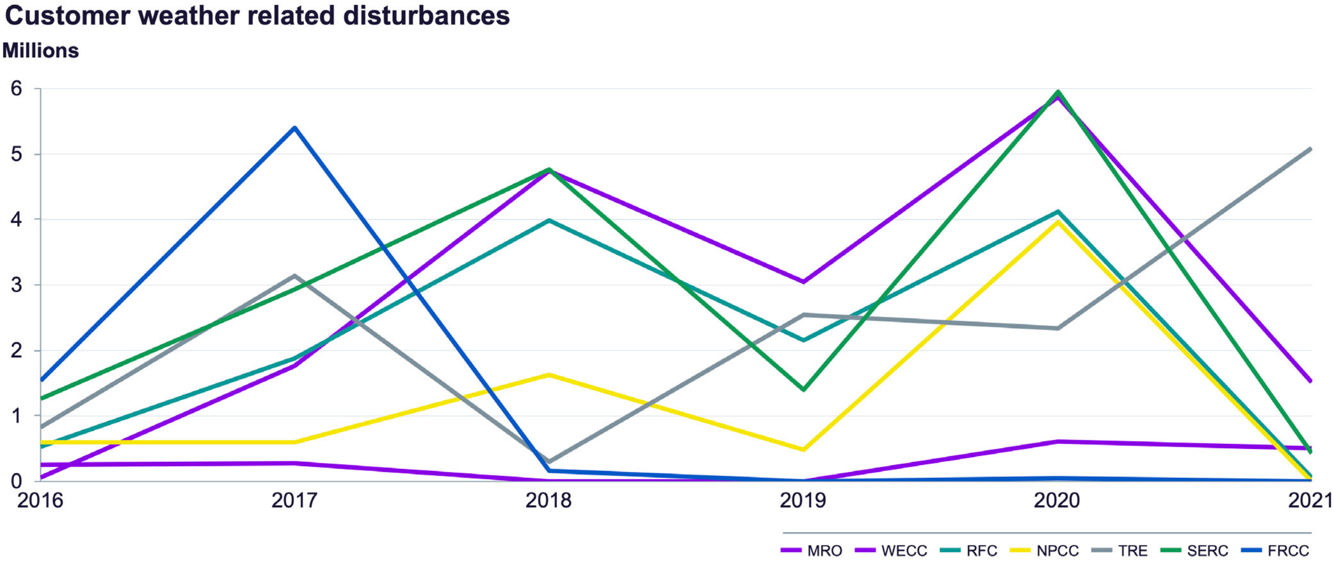


Figure D.1 Weather related disturbances by key NERC regions. Millions of customers impacted shown on the left.

When looking at a comparison of systems, the total number of customers impacted within the ERCOT (TRE) region is significant, but overall, it ranks fourth in scale of events to occur in the continental U.S. power grid. Reliability First Corporation (RFC) reported a maximum of 8 million customers impacted in a single month over the ten-year period. These figures in Table D.3 were determined by finding the maximum value for the month in question across a decade of events. (717,206 customers affected in 2011 was the maximum for that ten-year interval). For ERCOT (TRE) the maximum customer impact for any February was 2021.

Table D.3 Peak number of customers impacted by weather related events between 2011 and 2021.

	Maximum Weather Impact Customers (2011-2021)						
	WECC	TRE	NPCC	FRCC	MRO	SERC	RFC
January	1,170,997	188,000	80,000	-	-	1,355,716	717,206
February	383,841	4,905,248	229,247	-	503,107	826,404	1,203,739
March	270,332	274,414	826,313	137,000	-	498,181	2,619,203
April	318,719	629,967	408,476	49,999	-	2,519,719	389,591
May	2,800,426	655,269	436,049	-	-	538,073	647,388
June	4,200,000	1,218,017	135,442	-	593,000	1,188,526	8,071,881
July	82,000	333,208	158,131	-	250,000	440,540	1,625,066
August	2,924,268	2,782,636	2,556,179	440,000	610,000	2,192,914	3,701,163
September	1,666,500	65,000	155,000	5,397,555	-	1,882,683	564,400
October	1,874,210	752,037	2,720,891	1,365,000	-	1,851,199	3,393,050
November	571,000	-	178,408	-	-	628,448	841,146
December	433,970	881,000	290,231	-	34,500	380,872	238,304

Appendix E

E.1 Generation Modeling Results

The scenarios and simulations shown in this report have been defined using a base case scenario to simulate expected future meteorological conditions and system configuration. The simulations varied demand, renewable generation, and generator availability assumptions from a reference case. The simulations are performed using a combination of internal Siemens applications and an Aurora forecasting engine that is widely used in the US. The forecasting engine provides the least system cost solution for meeting the hourly demand under a given set of constraints.

The input assumptions on the supply side include:

- Generator additions and retirements
- Generator characteristics such as capacity, efficiency, ramp rates, planned and unplanned outage rates, and ancillary service capabilities.
- Renewable hourly capacity factor models
- Fuel prices
- Transmission Lines

The input assumptions on the demand side include:

- Hourly demand shape file per demand area
- Annual growth rates
- Ancillary Service Requirements

We performed multiple validations on the predicted vs. actual behavior as well as comparing expected market changes to third-party, government, and ISO source material.

The model explored for this study is zonal rather than nodal. It assumed the free flow of power within the demand areas but applied the expected transmission capacity limits between areas during the study time. This model used 8 demand areas: ERCOT North, ERCOT Houston, ERCOT South, ERCOT West, Austin Energy, CPS, Lower Colorado River Authority, and Rayburn.

Demand: The demand is determined using data from his Market.

Gas prices: Natural gas prices are adjusted using EIA (Energy Information Administration).

E.2 Scenario Definition

The report analyzes 3 different scenarios of extreme weather conditions. These include hot summers, cold winters, and extreme storms (hurricanes). In all the scenarios demand and generation are affected in different ways.

Appendix E

E.2.1 Heat Wave

The adjustments for the heat wave have been made using historical data of Hurricane Harvey that took place in Texas and Louisiana in August 2017. This scenario is simulated using August 2024 as a base case. The adjustments in demand and generation are done by zone and by fuel type in the case of generation for solar power plants. Natural gas and wind power plants have the historical outages from Hurricane Harvey applied. Following the historical evaluations, gas supply has not been constrained.

Demand will be adjusted by the following factors on the designated days. A 0.86 means the new demand will be the base case demand multiplied by a factor of 0.86.

Zone	Day 13	Day 14	Day 15	Day 16	Day 17
ERCOT-NOIE-AEN	0.86	0.73	0.73	0.86	0.93
ERCOT-NOIE-CPS	0.86	0.73	0.73	0.86	0.93
ERCOT-NOIE-LCRA	0.86	0.73	0.73	0.86	0.93
ERCOT-NOIE-Rayburn	0.89	0.77	0.77	0.89	1
ERCOT-Houston	0.86	0.71	0.71	0.86	0.93
ERCOT-North	0.89	0.77	0.77	0.89	1
ERCOT-South	0.78	0.73	0.73	0.78	0.89
ERCOT-West	0.95	0.89	0.89	0.95	1

Appendix E

Gas and wind power plants that went into an outage due to the damage of Hurricane Harvey are shown in the next table. Outage times have been divided in 4 buckets: plants that were in an outage for 1 day, for 2-7 days, for 7-14 days and for 14-21 days. A 1 in a bucket means the plant was off during that period of time. A null means it was online. Only power plants that went into an outage during the hurricane are shown in the table.

Site	Location	Fuel	Capacity	DAY 13	DAY 14-20	DAY 21-27	DAY 27-31
Freeport Energy Center	Greater Houston	NG	259	1	1	1	1
Freeport Power (Oyster Creek)	Greater Houston	NG	430	1	1	1	1
Dow Chemical Texas	Greater Houston	NG	565	1	1	1	
Chocolate Bayou Wind Project	Greater Houston	Wind	150	1			
Crawfish Wind Project	Greater Houston	Wind	153	1			
Exxon Baytown	Houston	NG	561	1	1		
Baytown Power Plant	Houston	NG	845	1	1		
Cedar Bayou	Houston	NG	1495	1	1		
Cedar Bayou 4	Houston	NG	599	1	1		
Bayou Cogen	Houston	NG	457	1	1		
Bacliff Peakers	Houston	NG	354	1	1		
Texas City	Houston	NG	484	1	1		
South Houston Green Power	Houston	NG	645	1	1		
Galveston Offshore Wind	Houston	Wind	300	1			
CFB Power Plant	South TX	NG	286	1	1	1	1
Gregory Power	South TX	NG	411	1	1	1	1
Nueces Bay Repower	South TX	NG	655	1	1	1	1

Appendix E

Site	Location	Fuel	Capacity	DAY 13	DAY 14-20	DAY 21-27	DAY 27-31
Nueces Bay Repower	South TX	NG	655	1	1	1	1
Corprus Christi	South TX	NG	485	1	1	1	1
Barney Davis	South TX	NG	655	1	1	1	1
Formosa Utility Venture	South TX	NG	954	1	1	1	
Ingleside Cogen	South TX	NG	508	1	1	1	
Peyton Creek Wind Farm	South TX	Wind	151	1			
Karankawa Wind Project	South TX	Wind	380	1			
Carnell Wind Farm Project	South TX	Wind	220	1			
Midway Wind Project	South TX	Wind	163	1			
Papalote Creek Wind Facility II	South TX	Wind	201	1			
Papalote Creek Wind Facility	South TX	Wind	180	1			
Harbor Wind Project	South TX	Wind	9	1			
Shaffer Wind Project	South TX	Wind	226	1			
SANTACRU (Chapman Rand Wind)	South TX	Wind	249	1			
Penascall III Wind Project	South TX	Wind	188	1			
Penascall II Wind Project	South TX	Wind	201	1			
Penascall Wind Project	South TX	Wind	201	1			
Texas Gulf Wind Repower	South TX	Wind	271	1			
Stella Wind Farm	South TX	Wind	201	1			

Appendix E

Site	Location	Fuel	Capacity	DAY 13	DAY 14-20	DAY 21-27	DAY 27-31
Las Majadas Wind Project	South TX	Wind	272	1			
Palmas Atlas Wind Project	South TX	Wind	145	1			
San Roman Wind	South TX	Wind	95	1			
Los Vientos Wind 1A	South TX	Wind	200	1			
Blackjack Creek	South TX	Wind	240	1			
El Algodon Wind Farm	South TX	Wind	200	1			
Texas Gulf Wind II	South TX	Wind	226	1			

Solar power plants have been affected by zone and by day. The following table shows the adjustments that have been made to these plants. A 0.33 on a given day for a given zone would mean a reduction of 67% of the resource for that given day and that given zone.

Zone	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	Day 19
ERCOT-NOIE-AEN	1	1	1	1	1	1	1
ERCOT-NOIE-CPS	1	1	1	1	1	1	1
ERCOT-NOIE-LCRA	1	1	1	1	1	1	1
ERCOT-NOIE-Rayburn	1	1	1	1	1	1	1
ERCOT-Houston	0.33	0.33	0.6	0.6	0.8	0.92	1
ERCOT-North	1	1	0.5	0.5	0.6	0.8	0.8
ERCOT-South	0.25	0.25	0.4	0.4	0.73	0.9	1
ERCOT-West	1	1	1	1	1	1	1

Once the adjustments made, the simulation is run using an optimization software that predicts the dispatch in the system.

Appendix E

E.2.2 Cold Wave

The adjustments for the cold wave have been made using historical data from the Winter Storm Uri that took place in February 2021 in North America.

This scenario is simulated using February 2024 as a base case. Three scenarios with the same demand and different supply have been modeled in this case:

1. Medium natural gas availability and low renewables availability
2. Medium natural gas and wind availability and high sun availability
3. High gas availability and low renewables availability

The adjustments in demand and generation are done by zone and by fuel type in the case of generation. Following the historical evaluations, gas supply has not been constrained.

Demand is adjusted by the following factors on the designated days. A 1.12 means the new demand will be the base case demand multiplied by a factor of 1.12.

Zone	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11
ERCOT-NOIE-AEN	1.12	1.38	1.47	1.47	1.37	1.28	1.2
ERCOT-NOIE-CPS	1.12	1.38	1.47	1.47	1.37	1.28	1.2
ERCOT-NOIE-LCRA	1.12	1.38	1.47	1.47	1.37	1.28	1.2
ERCOT-NOIE-Rayburn	1.12	1.38	1.47	1.47	1.37	1.28	1.2
ERCOT-Houston	1.12	1.38	1.47	1.47	1.37	1.28	1.2
ERCOT-North	1.12	1.38	1.47	1.47	1.37	1.28	1.2
ERCOT-South	1.12	1.38	1.47	1.47	1.37	1.28	1.2
ERCOT-West	1.12	1.38	1.47	1.47	1.37	1.28	1.2

Appendix E

The 3 scenarios for supply are described as follows:

E.2.2.1 Scenario 1

The generation technologies by fuel type that have been affected are natural gas, coal, wind and solar.

For natural gas and coal power plants, the available capacity has been reduced by a percentage. A 0.5 in the following table means that 50% of the capacity will be available for the natural gas power plants in that day and zone.

The adjustments applied to natural gas are the following:

Zone	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11
ERCOT-NOIE-AEN	1	1	0.5	0.5	1	1	1
ERCOT-NOIE-CPS	1	1	0.5	0.5	1	1	1
ERCOT-NOIE-LCRA	1	1	0.5	0.5	1	1	1
ERCOT-NOIE-Rayburn	1	1	0.5	0.5	1	1	1
ERCOT-Houston	1	1	0.5	0.5	1	1	1
ERCOT-North	1	1	0.5	0.5	1	1	1
ERCOT-South	1	1	0.5	0.5	1	1	1
ERCOT-West	1	1	0.5	0.5	1	1	1

Appendix E

The adjustments applied to coal are the following:

Zone	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11
ERCOT-NOIE-AEN	1	1	0.85	0.85	1	1	1
ERCOT-NOIE-CPS	1	1	0.85	0.85	1	1	1
ERCOT-NOIE-LCRA	1	1	0.85	0.85	1	1	1
ERCOT-NOIE-Rayburn	1	1	0.85	0.85	1	1	1
ERCOT-Houston	1	1	0.3	0.3	1	1	1
ERCOT-North	1	1	0.7	0.7	1	1	1
ERCOT-South	1	1	0.85	0.85	1	1	1
ERCOT-West	1	1	1	1	1	1	1

Wind and solar power plants will get their sun and wind reduced respectively. A 0.66 on a given day for a given zone would mean a reduction of 44% of the resource for that given day and that given zone.

The adjustments applied to wind are the following:

Zone	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11
ERCOT-NOIE-AEN	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-NOIE-CPS	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-NOIE-LCRA	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-NOIE-Rayburn	1	1	0	0	0	0	0
ERCOT-Houston	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-North	1	1	0	0	0	0	0
ERCOT-South	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-West	1	1	0	0	0	0	0

Appendix E

The adjustments applied to solar are the following:

Zone	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12
ERCOT-NOIE-AEN	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-NOIE-CPS	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-NOIE-LCRA	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-NOIE-Rayburn	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-Houston	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-North	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-South	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-West	1	1	0.3	0.26	0.25	0.5	0.6	0.65

Appendix E

E.2.2.2 Scenario 2

The generation technologies by fuel type that have been affected are natural gas, coal, wind and solar.

For natural gas and coal power plants, the available capacity has been reduced by a percentage. A 0.5 in the following table means that 50% of the capacity will be available for the natural gas power plants in that day and zone.

The adjustments applied to natural gas are the following:

Zone	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11
ERCOT-NOIE-AEN	1	1	0.5	0.5	1	1	1
ERCOT-NOIE-CPS	1	1	0.5	0.5	1	1	1
ERCOT-NOIE-LCRA	1	1	0.5	0.5	1	1	1
ERCOT-NOIE-Rayburn	1	1	0.5	0.5	1	1	1
ERCOT-Houston	1	1	0.5	0.5	1	1	1
ERCOT-North	1	1	0.5	0.5	1	1	1
ERCOT-South	1	1	0.5	0.5	1	1	1
ERCOT-West	1	1	0.5	0.5	1	1	1

The adjustments applied to coal are the following:

Zone	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11
ERCOT-NOIE-AEN	1	1	0.85	0.85	1	1	1
ERCOT-NOIE-CPS	1	1	0.85	0.85	1	1	1
ERCOT-NOIE-LCRA	1	1	0.85	0.85	1	1	1
ERCOT-NOIE-Rayburn	1	1	0.85	0.85	1	1	1
ERCOT-Houston	1	1	0.3	0.3	1	1	1
ERCOT-North	1	1	0.7	0.7	1	1	1
ERCOT-South	1	1	0.85	0.85	1	1	1
ERCOT-West	1	1	1	1	1	1	1

Appendix E

Wind and solar power plants will get their sun and wind reduced respectively. A 0.66 on a given day for a given zone would mean a reduction of 44% of the resource for that given day and that given zone.

The adjustments applied to wind are the following:

Zone	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11
ERCOT-NOIE-AEN	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-NOIE-CPS	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-NOIE-LCRA	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-NOIE-Rayburn	1	1	0	0	0	0	0
ERCOT-Houston	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-North	1	1	0	0	0	0	0
ERCOT-South	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-West	1	1	0	0	0	0	0

The adjustments applied to solar are the following:

Zone	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11
ERCOT-NOIE-AEN	1	1	0.95	1	1	1	1
ERCOT-NOIE-CPS	1	1	0.95	1	1	1	1
ERCOT-NOIE-LCRA	1	1	0.95	1	1	1	1
ERCOT-NOIE-Rayburn	1	1	0.95	1	1	1	1
ERCOT-Houston	1	1	0.95	1	1	1	1
ERCOT-North	1	1	0.95	1	1	1	1
ERCOT-South	1	1	0.95	1	1	1	1
ERCOT-West	1	1	0.95	1	1	1	1

Appendix E

E.2.2.3 Scenario 3

The generation technologies by fuel type that have been affected are coal, wind and solar.

For coal power plants, the available capacity has been reduced by a percentage. A 0.5 in the following table means that 50% of the capacity will be available for the natural gas power plants in that day and zone.

The adjustments applied to coal are the following:

Zone	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11
ERCOT-NOIE-AEN	1	1	0.85	0.85	1	1	1
ERCOT-NOIE-CPS	1	1	0.85	0.85	1	1	1
ERCOT-NOIE-LCRA	1	1	0.85	0.85	1	1	1
ERCOT-NOIE-Rayburn	1	1	0.85	0.85	1	1	1
ERCOT-Houston	1	1	0.3	0.3	1	1	1
ERCOT-North	1	1	0.7	0.7	1	1	1
ERCOT-South	1	1	0.85	0.85	1	1	1
ERCOT-West	1	1	1	1	1	1	1

Appendix E

Wind and solar power plants will get their sun and wind reduced respectively. A 0.66 on a given day for a given zone would mean a reduction of 44% of the resource for that given day and that given zone.

The adjustments applied to wind are the following:

Zone	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11
ERCOT-NOIE-AEN	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-NOIE-CPS	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-NOIE-LCRA	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-NOIE-Rayburn	1	1	0	0	0	0	0
ERCOT-Houston	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-North	1	1	0	0	0	0	0
ERCOT-South	1	1	0.7	0.6	0.5	0.5	0.6
ERCOT-West	1	1	0	0	0	0	0

The adjustments applied to solar are the following:

Zone	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12
ERCOT-NOIE-AEN	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-NOIE-CPS	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-NOIE-LCRA	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-NOIE-Rayburn	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-Houston	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-North	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-South	1	1	0.3	0.26	0.25	0.5	0.6	0.65
ERCOT-West	1	1	0.3	0.26	0.25	0.5	0.6	0.65

Appendix E

E.2.3 Hurricane

The adjustments for the heat wave have been made using historical data of Hurricane Harvey that took place in Texas and Louisiana in August 2017.

This scenario is simulated using August 2024 as a base case. The adjustments in demand and generation are done by zone and by fuel type in the case of generation for solar power plants. Natural gas and wind power plants have the historical outages from Hurricane Harvey applied. Following the historical evaluations, gas supply has not been constrained.

Demand will be adjusted by the following factors on the designated days. A 0.86 means the new demand will be the base case demand multiplied by a factor of 0.86.

Zone	Day 13	Day 14	Day 15	Day 16	Day 17
ERCOT-NOIE-AEN	0.86	0.73	0.73	0.86	0.93
ERCOT-NOIE-CPS	0.86	0.73	0.73	0.86	0.93
ERCOT-NOIE-LCRA	0.86	0.73	0.73	0.86	0.93
ERCOT-NOIE-Rayburn	0.89	0.77	0.77	0.89	1
ERCOT-Houston	0.86	0.71	0.71	0.86	0.93
ERCOT-North	0.89	0.77	0.77	0.89	1
ERCOT-South	0.78	0.73	0.73	0.78	0.89
ERCOT-West	0.95	0.89	0.89	0.95	1

Appendix E

Gas and wind power plants that went into an outage due to the damage of Hurricane Harvey are shown in the next table. Outage times have been divided in 4 buckets: plants that were in an outage for 1 day, for 2-7 days, for 7-14 days and for 14-21 days. A 1 in a bucket means the plant was off during that period of time. A null means it was online. Only power plants that went into an outage during the hurricane are shown in the table.

Site	Location	Fuel	Capacity	DAY 13	DAY 14-20	DAY 21-27	DAY 27-31
Freeport Energy Center	Greater Houston	NG	259	1	1	1	1
Freeport Power (Oyster Creek)	Greater Houston	NG	430	1	1	1	1
Dow Chemical Texas	Greater Houston	NG	565	1	1	1	
Chocolate Bayou Wind Project	Greater Houston	Wind	150	1			
Crawfish Wind Project	Greater Houston	Wind	153	1			
Exxon Baytown	Houston	NG	561	1	1		
Baytown Power Plant	Houston	NG	845	1	1		
Cedar Bayou	Houston	NG	1495	1	1		
Cedar Bayou 4	Houston	NG	599	1	1		
Bayou Cogen	Houston	NG	457	1	1		
Bacliff Peakers	Houston	NG	354	1	1		
Texas City	Houston	NG	484	1	1		
South Houston Green Power	Houston	NG	645	1	1		
Galveston Offshore Wind	Houston	Wind	300	1			
CFB Power Plant	South TX	NG	286	1	1	1	1
Gregory Power	South TX	NG	411	1	1	1	1
Nueces Bay Repower	South TX	NG	655	1	1	1	1

Appendix E

Site	Location	Fuel	Capacity	DAY 13	DAY 14-20	DAY 21-27	DAY 27-31
Corprus Christi	South TX	NG	485	1	1	1	1
Barney Davis	South TX	NG	655	1	1	1	1
Formosa Utility Venture	South TX	NG	954	1	1	1	
Ingleside Cogen	South TX	NG	508	1	1	1	
Peyton Creek Wind Farm	South TX	Wind	151	1			
Karankawa Wind Project	South TX	Wind	380	1			
Carnell Wind Farm Project	South TX	Wind	220	1			
Midway Wind Project	South TX	Wind	163	1			
Papalote Creek Wind Facility II	South TX	Wind	201	1			
Papalote Creek Wind Facility	South TX	Wind	180	1			
Harbor Wind Project	South TX	Wind	9	1			
Shaffer Wind Project	South TX	Wind	226	1			
SANTACRU (Chapman Rand Wind)	South TX	Wind	249	1			
Penascall III Wind Project	South TX	Wind	188	1			
Penascall II Wind Project	South TX	Wind	201	1			
Penascall Wind Project	South TX	Wind	201	1			
Texas Gulf Wind Repower	South TX	Wind	271	1			
Stella Wind Farm	South TX	Wind	201	1			
Las Majadas Wind Project	South TX	Wind	272	1			

Appendix E

Site	Location	Fuel	Capacity	DAY 13	DAY 14-20	DAY 21-27	DAY 27-31
Palmas Atlas Wind Project	South TX	Wind	145	1			
San Roman Wind	South TX	Wind	95	1			
Los Vientos Wind 1A	South TX	Wind	200	1			
Blackjack Creek	South TX	Wind	240	1			
El Algodon Wind Farm	South TX	Wind	200	1			
Texas Gulf Wind II	South TX	Wind	226	1			

Solar power plants have been affected by zone and by day. The following table shows the adjustments that have been made to these plants. A 0.33 on a given day for a given zone would mean a reduction of 67% of the resource for that given day and that given zone.

Zone	Day 13	Day 14	Day 15	Day 16	Day 17	Day 18	D
ERCOT-NOIE-AEN	1	1	1	1	1	1	1
ERCOT-NOIE-CPS	1	1	1	1	1	1	1
ERCOT-NOIE-LCRA	1	1	1	1	1	1	1
ERCOT-NOIE-Rayburn	1	1	1	1	1	1	1
ERCOT-Houston	0.33	0.33	0.6	0.6	0.8	0.92	1
ERCOT-North	1	1	0.5	0.5	0.6	0.8	0
ERCOT-South	0.25	0.25	0.4	0.4	0.73	0.9	1
ERCOT-West	1	1	1	1	1	1	1

Once the adjustments made, the simulation is run using an optimization software that predicts the dispatch in the system.

Appendix E

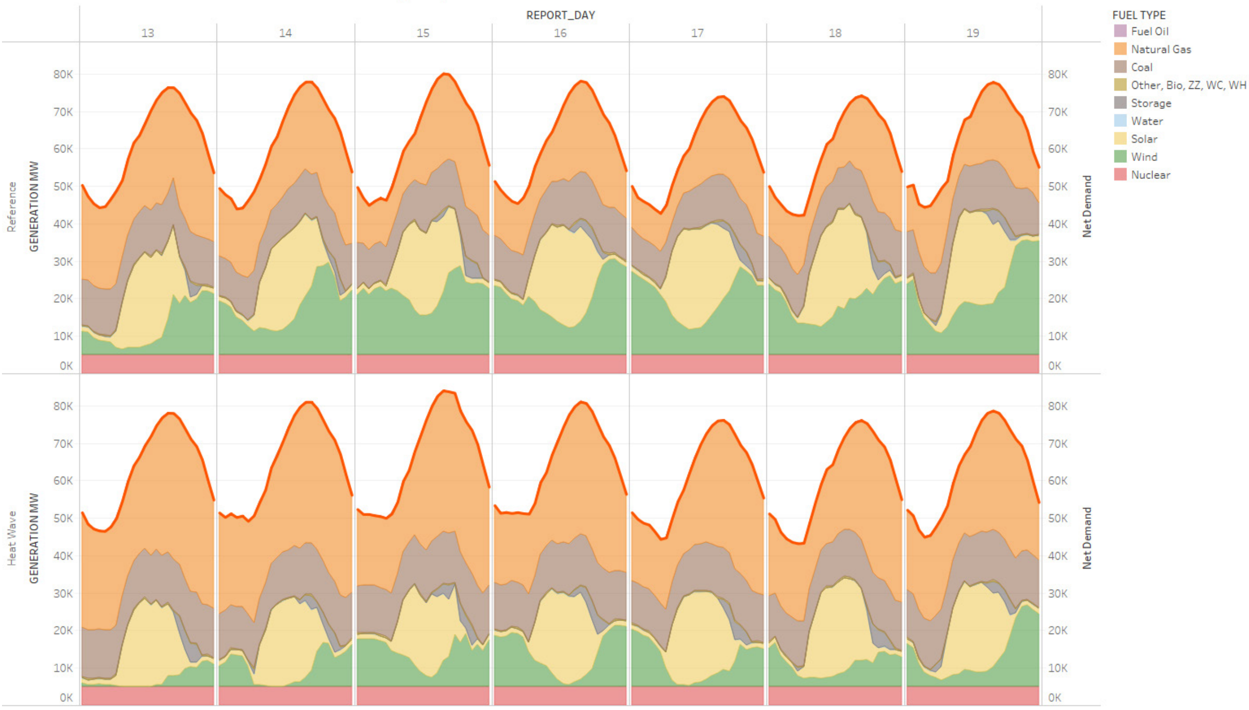
E.3 Results

The optimization software outputs the power plant dispatch at an hourly and unit level for the reference case and the scenario applied. Extremes of high and low temperatures are considered here.

E.3.1 Heat Wave

The following dashboard compares the dispatch by fuel type for the reference case and the heat wave scenario for the whole system. Demand is shown with a red line.

Heat Wave Generation by fuel type vs Demand [MW]



The trends of sum of GENERATION_MWH and sum of Net Demand for REPORT_HOUR broken down by REPORT_DAY vs. RUN_ID. For pane Sum of GENERATION_MWH: Color shows details about PRIMARY_FUEL (group). The data is filtered on FILENAME, which keeps ERCOT_WhitePaper_Heat_Wave_08042021_3. The view is filtered on PRIMARY_FUEL (group) and REPORT_DAY. The PRIMARY_FUEL (group) filter has multiple members selected. The REPORT_DAY filter keeps 7 of 31 members.

As the dashboard shows, during the days the heat wave occurs, demand is increased, peaking above 84 GW on August 15th against the peak in the reference case that was under 80 GW.

Constraints in renewable energy sources, especially in wind, lead to a significant lack of supply by these technologies supply during the event. However, gas and coal power plants compensate for this lack of wind allowing the demand to be met even with these extreme conditions.

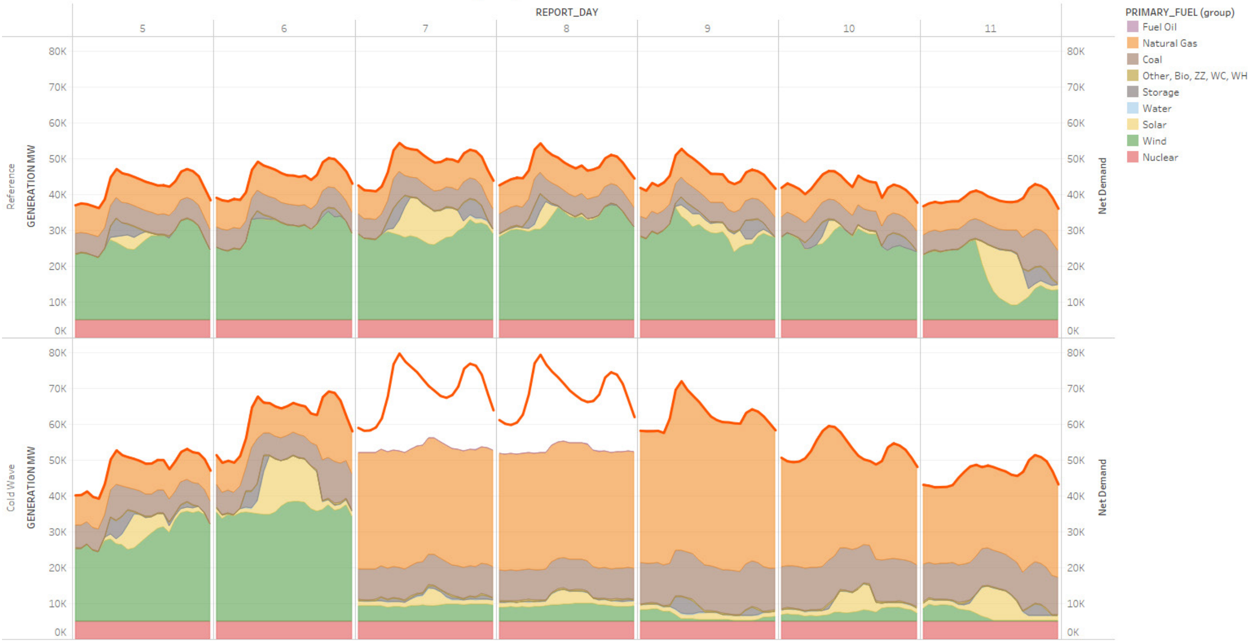
Appendix E

E.3.2 Cold Wave

Scenario 1

The following dashboard compares the dispatch by fuel type for the reference case and the heat wave scenario for the whole system. Demand is shown with a red line.

Subscenario 1: Cold Wave Generation by fuel type vs Demand [MW]



The trends of sum of GENERATION_MWH and sum of Net Demand for REPORT_HOUR broken down by REPORT_DAY vs. RUN_ID. For pane Sum of GENERATION_MWH: Color shows details about PRIMARY_FUEL (group). The data is filtered on FILENAME, which keeps ERCOT_WhitePaper_Cold_Wave_08052021_3. The view is filtered on PRIMARY_FUEL (group) and REPORT_DAY. The PRIMARY_FUEL (group) filter has multiple members selected. The REPORT_DAY filter keeps 7 of 31 members.

As the dashboard shows, during the days the cold wave occurs, demand increases, peaking at 80 GW on February 6th and 7th against the peak in the reference case that was under 54 GW.

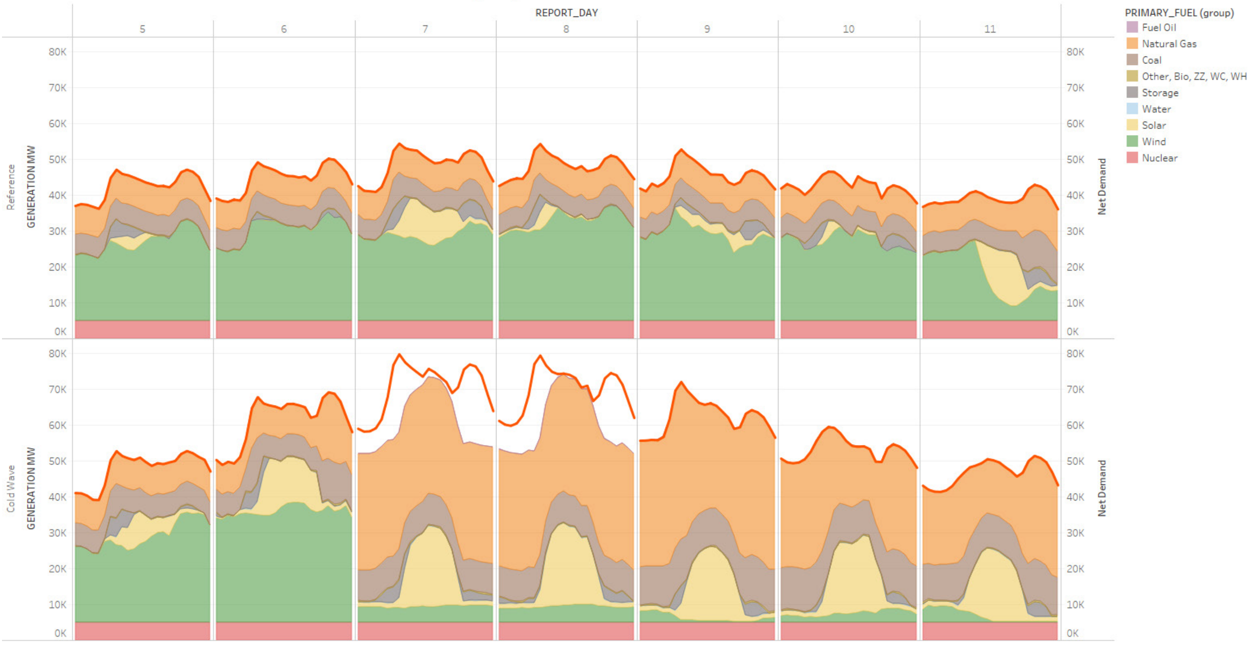
Limitations on gas, coal and renewable power plants prevents the supply from meeting the demand. The amount of demand not met during February 7th and 8th has a minimum of 6 GW and a maximum of 28 GW.

Appendix E

Scenario 2

The following dashboard compares the dispatch by fuel type for the reference case and the heat wave scenario for the whole system. Demand is shown with a red line.

Subscenario 2: Cold Wave Generation by fuel type vs Demand [MW]



The trends of sum of GENERATION_MWH and sum of Net Demand for REPORT_HOUR broken down by REPORT_DAY vs. RUN_ID. For pane Sum of GENERATION_MWH: Color shows details about PRIMARY_FUEL (group). The data is filtered on FILENAME, which keeps ERCOT_WhitePaper_Cold_Wave_08052021_1. The view is filtered on PRIMARY_FUEL (group) and REPORT_DAY. The PRIMARY_FUEL (group) filter has multiple members selected. The REPORT_DAY filter keeps 7 of 31 members.

In this second scenario, demand is the same as in the previous one.

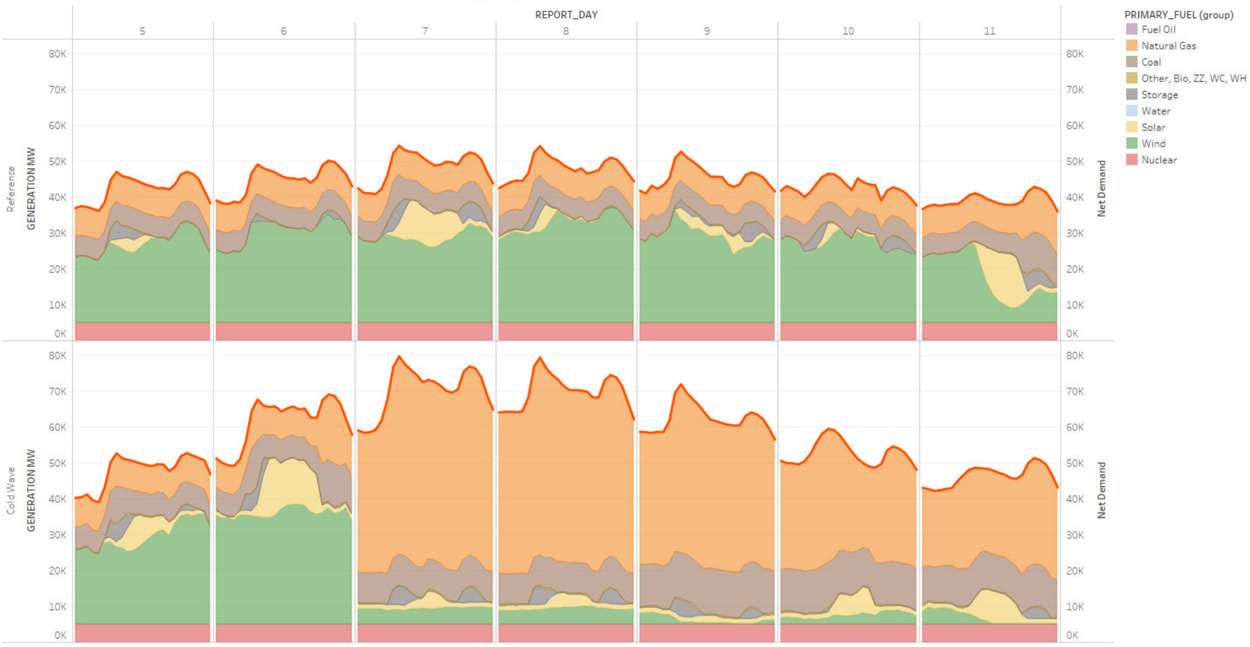
Limitations on gas, coal and renewable power plants prevents the supply from meeting the demand. In this case, the amount of demand not met during February 7th and 8th has a minimum of 0 GW and a maximum of 6 GW. Solar power plants being limited very little are the ones that allow to meet the demand at some point during those extreme days.

Appendix E

Scenario 3

The following dashboard compares the dispatch by fuel type for the reference case and the heat wave scenario for the whole system. Demand is shown with a red line and the cold wave period in a blue box.

Subscenario 3: Cold Wave Generation by fuel type vs Demand [MW]



The trends of sum of GENERATION_MWH and sum of Net Demand for REPORT_HOUR broken down by REPORT_DAY vs. RUN_ID. For pane Sum of GENERATION_MWH: Color shows details about PRIMARY_FUEL (group). The data is filtered on FILENAME, which keeps ERCOT_WhitePaper_Cold_Wave_09012021_1. The view is filtered on PRIMARY_FUEL (group) and REPORT_DAY. The PRIMARY_FUEL (group) filter has multiple members selected. The REPORT_DAY filter keeps 7 of 31 members.

In this second scenario, demand is the same as in the previous one.

The non-limitation of gas power plants allows the supply to meet the demand.

Appendix E

E.4 Conclusions

The following table sums up the type of constraints applied to the different power plants by fuel type and scenario.

Fuel type	scenario 1	scenario 2	scenario 3
Natural Gas	Medium	Medium	None
Coal	Medium	Medium	Medium
Wind	High	High	High
Sun	High	Low	High

The next table sums up in which scenarios the demand was met by the generation.

scenario	Demand met
1	No
2	No
3	Yes

The capacity added by fuel type in the reference case since January 2022 until 2024 are the following:

Fuel Grouping	Total Capacity Added [MW]
Natural Gas	700
Solar	19,796.15
Wind	3,839.02
STORAGE	2,764.82

The capacity retired is the following:

Fuel Grouping	Total Capacity RETIRED [MW]
Natural Gas	663

Appendix E

Since Winter Storm Uri happened in 2021 until 2024 natural gas capacity installed is expected to remain almost constant. Renewable additions to the system are expected to increase by the following:

Solar **20 GW**

Wind **4 GW**

Storage 3 GW

The three scenarios run show that without renewable power plants running and with an increase in the demand, the generation is only able to supply demand if all the gas power plants are available. Winterization of these power plants would increase its availability in these types of situations. In scenario 2, low constraints for solar power plants allow supply to meet demand for a few hours.

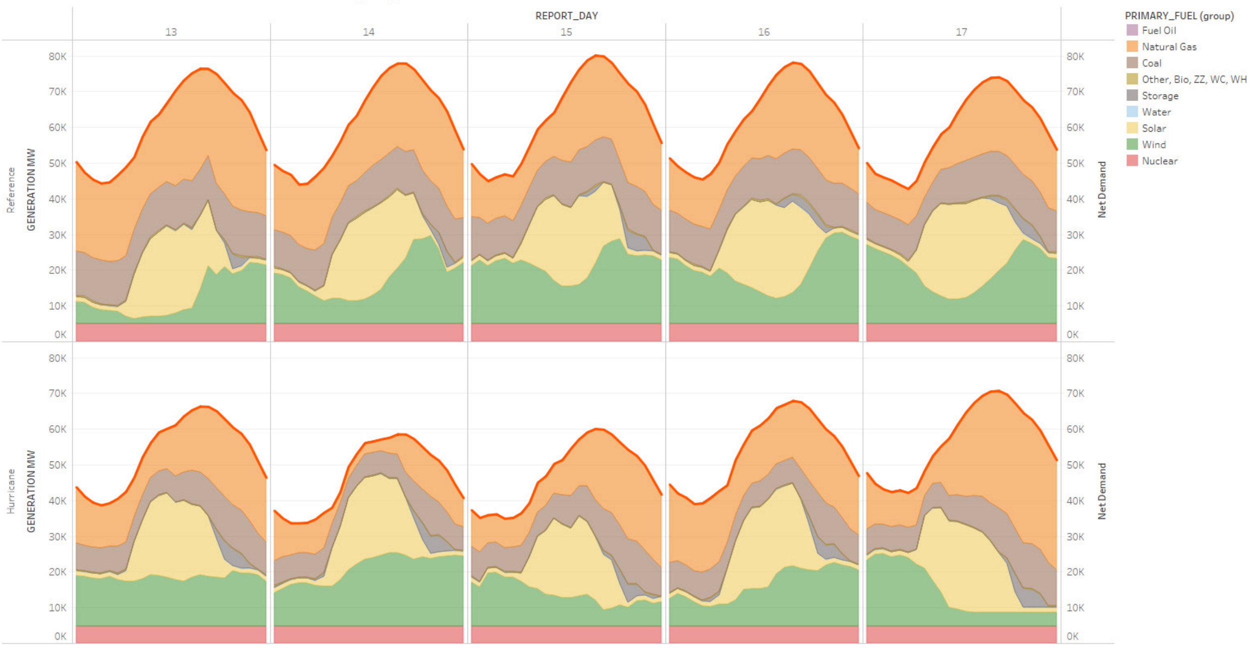
Increases in solar and wind capacity do not guarantee that demand can be met in all cases. Storage additions are not expected to be sufficient at the levels noted. Having wind power plants winterized would be an additional help for the overall supply.

Hurricane

The following dashboard compares the dispatch by fuel type for the reference case and the heat wave scenario for the whole system. Demand is shown with a red line and the hurricane period in a blue box.

As the dashboard show, during the hurricane, demand decreases hitting the minimum daily peak on August 14th under 60 GW against the over 75 GW in the reference case. Due to the significant reduction in demand the remaining resources are able to meet the demand need even with the reduction of available resources by 15 GW.

Hurricane Generation by fuel type vs Demand [MW]



The trends of sum of GENERATION_MWH and sum of Net Demand for REPORT_HOUR broken down by REPORT_DAY vs. RUN_ID. For pane Sum of GENERATION_MWH: Color shows details about PRIMARY_FUEL (group). The data is filtered on FILENAME, which keeps ERCOT_WhitePaper_Hurricane_08172021_3. The view is filtered on PRIMARY_FUEL (group) and REPORT_DAY. The PRIMARY_FUEL (group) filter has multiple members selected. The REPORT_DAY filter keeps 13, 14, 15, 16 and 17.

Appendix F

F.1 Gas Turbine Modifications and Improvements

There are several technologies that can be implemented to ensure natural gas and oil-fired power plants perform in extreme weather conditions. The following sections highlight some of the component specific solutions that can be implemented to make power plants winter weather ready. To increase the availability of the power plants or to satisfy regulatory requirements, there are solutions which reduce the impact of natural gas shortages during extreme weather events.

F.2 Fuel Systems

A dual fuel setup for example enables the gas turbine to switch over to burning fuel oil stored on-site in case the natural gas supply is interrupted. Solutions may include fuel oil forwarding, fuel conditioning skids, and dual fuel burners. To ensure the dual fuel system is available when needed, it should be well maintained and regularly inspected and tested.

To reduce the required amount of natural gas and align with decarbonization goals, new solutions for hydrogen co-firing or alternate fuels should be deployed while older units should be retrofitted with the required equipment as well.

F.3 Gas Turbine Air Inlet Systems

For power plants which are expected to run during heavy snow fall, inlet filter structures equipped with low velocity hoods will reduce the amount of snow drawn into the filters. In addition, a pulse filter system can be installed which, with the use of compressed air, generates pulses in the filter elements and therefore prevents any snow or ice buildup.

To prevent condensation and ice forming on the inside of the air inlet, units to be operated in cold weather are equipped with inlet-heating or anti-icing systems. To heat the inlet air, hot compressor bleed air is routed into the inlet structure through a sparger. This system can heat up the inlet air by an additional 11°F and is automatically turned on when the system determines that the ambient temperature and humidity may cause ice build-up. These systems can retrofitted on existing assets of varying configurations.

For lower ambient temperatures, an inlet heating system must be provided to prevent the inlet air temperature at the compressor inlet from dropping below -5°F or below -20°F. These systems can utilize either compressor bleed air or a glycol heat exchanger with an external heat source. If the air at the compressor inlet drops below these limits (there may be project specific exceptions) the turbine will trip to prevent brittle fractures (fatigue) of the turbine rotor.

F.4 Gas Turbine Enclosure

To protect the gas turbine and any equipment and piping in the immediate vicinity from cold weather, turbine enclosures can be erected with insulation and heaters designed to keep the internal temperature above 40°F.

Appendix F

F.5 Heat Recovery Steam Generator (HRSG)

Most of the critical components of an HRSG are located on the top, near the steam drums and headers. These components include drum level, pressure and flow transmitters which are critical for the operation of the respective gas turbine train. Their location makes these components very susceptible to freezing because of their exposure to temperature and especially to wind. Access on top of the HRSG is more difficult during operation and maintenance making trouble shooting and repairs during an extreme weather event challenging if not dangerous.

Depending on the minimum design temperature and expected wind exposure, these components need to be protected with either heat tracing and insulation, an enclosure, or both. Solutions can vary from small individual enclosures over drum-end to full drum enclosures. Depending on the ambient conditions, and customer preferences, these enclosures can act simply as wind protection or be fully insulated and heated. The remaining piping, instruments and valves should be heat traced and insulated to prevent freezing, with added wind protection for especially exposed components.

F.6 Steam Turbine

Large steam turbines need to be warmed up to a metal temperature of at least 41°F before they can be started. Warming can be achieved via the circulation of heated lift, seal, and lube oil.

To reduce the required time for warm-up after a long outage, heated turbine enclosures or heating blanket systems can be installed.

F.6.1 Electrical Generator

Air cooled generators can be equipped with space heaters to prevent condensation in the generator or exciter.

F.6.2 Turbine and Generator Skids

The lube oil skid(s), consisting of a tank, pumps and filters includes a tank heater to meet oil viscosity requirements. Typically, depending on the oil specification, any lube, seal or lift oil in the tank or piping needs to be heated to at least 40°F to meet process requirements. For ambient temperatures near zero Fahrenheit control oil piping and tanks should also be heated to achieve sufficient viscosity.

Water or steam service skids used for compressor wash, water injection, stator water cooling, gland steam condensing and others will require freeze protection to maintain a fluid temperature of at least 40°F. Depending on the configuration of these skids and access requirements, heated enclosures or heat tracing are available solutions to prevent freezing.

Appendix F

F.6.3 Turbine and Generator Piping

All water or steam filled piping and tubing around gas turbines, steam turbines and electrical generators should be heat traced and insulated to maintain a fluid temperature of at least 40°F.

In addition, lube, lift and seal oil piping typically requires heat tracing to meet oil viscosity requirements.

Similarly fuel oil piping needs to be heat traced to maintain it above its pour point, typically 20°F. Critical during extreme cold weather, to allow at least two aborted starts, a sufficient length of piping needs to be heated to at least 80°F to have enough pre-heated oil to support ignition.

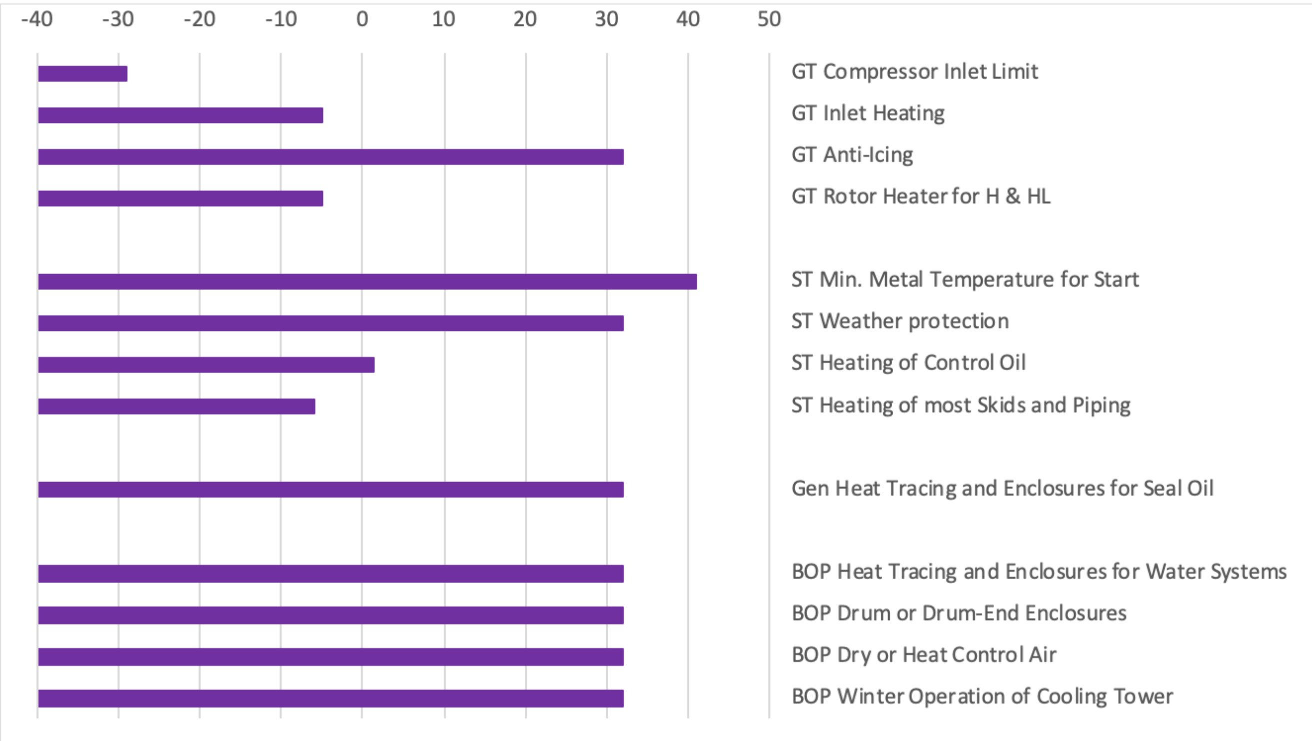


Figure F.1 Typical Temperature Limits of Plant Equipment [°F].

Appendix F

F.6.4 Balance of Plant

An experienced power plant OEM s provider can design, supply, and install plant-wide freeze protection solutions as described in the following sub sections.

F.6.5 Instruments and Monitoring Systems

Many instruments are critical for operating or starting a power plant and at the same time their small size makes them vulnerable to freezing if exposed to cold weather.

For pressure, differential pressure, flow or level instruments, their respective transmitters should be mounted in a heated and insulated enclosure. Gauges should either be protected with heat tracing and insulation or placed inside of enclosures.

Equally critical are the sensing lines and instrument root valves which are also small, exposed, and very vulnerable to freezing. It is recommended to use pre-insulated, and heat traced tubing for all sensing and sampling lines which provide superior water tightness and longevity compared to field installed tracing and insulation. Special care needs to be taken at transitions between tubing and piping to ensure that tracer cable overlaps and insulation jacketing seams are watertight.

F.6.6 Control Air

To ensure the power plant can start, operate, or safely shutdown it is vital to have a reliable source of control air. Supplied systems should be equipped with dryers which dry the air to a dew point much lower than the lowest anticipated ambient temperature. Alternatively, critical sections of the control air distribution piping can be heat traced and insulated to prevent condensation and subsequent icing.

F.6.7 Piping and Components

If there is a chance of freezing, all exposed small-bore piping and tubing need to be protected by heat tracing and insulation. Larger piping needs to be protected from freezing if the pipe cannot be drained, if there is no flow during operation, or if the design temperature is low enough for freezing to occur even during operation.

Appendix F

Figure F.2 Natural gas fueled combined cycle plant equipped for winter operation in the United States.

Valves are typically protected with heat tracing and insulation, similar to the connected piping, however some valves may require special solutions depending on their design. Back flow preventers with test connections should instead be in a hot box to prevent freezing and allow regular access. Due to external impulse lines, heat tracing may not be practical for medium controlled valves like pressure regulators, and instead they may rather be installed in a heated and insulated valve box.

Some piping systems, typically closed cooling water, can also be protected from freezing by using a water-glycol mix. To ensure the system works as designed, the glycol concentration should be checked regularly and maintained at the level determined by the designer. A too low concentration makes the system more vulnerable to freezing while a too high level reduces the capability of the system to transport heat and cool equipment.

Appendix F

F.6.8 Heat Tracing System

Power generators rely mostly on electrical heat tracing for freeze protection. To achieve high availability during cold weather, it is important that this system provides detailed feedback to the operator and is designed considering trouble shooting and maintenance.

For example, heat tracing control panels should indicate faults like loss of power but also detect loss of branch voltage, continuity, and ground fault. Having this information available by branch allows operators to quickly determine which pipes and components are at risk of freezing and whether there is an immediate risk for plant operation. It also shortens the time required to trouble shoot and repair the system. Modern systems can also monitor branch current and voltage which are also helpful to ensure system integrity.

Another good practice is to limit the impact of branch failures by reducing the heater cable length as well as the amount of in series connected heaters. If possible, a single branch should only heat a single system or subsystem to again limit the impact in case of a failure.

Appendix G

G.1 Gas Modeling

The scenarios and simulations shown in this report have been defined using a base case scenario to simulate expected future meteorological conditions and system configuration. The simulations varied demand, gas production, and storage availability assumptions from a reference case.

General assumptions for gas supply include:

• Production decline of 3% year-over-year

• No expansions or retirement of storage facilities from 2021 levels (both Working Gas Capacity and Daily Deliverable Volumes)

General assumptions for infrastructure include:

• Intrastate Pipeline baseline capacities equal to nameplate.

• Storage sites near the Texas border were included in gas storage totals (Southeastern New Mexico, Western Oklahoma, Northwestern Louisiana).

General assumptions for demand include:

• Gas demand for Power Generation in ERCOT derived using energy generation modeling in same scenario.

• Gas demand outside of ERCOT derived from a baseline, with specific demand in various scenarios grossed up from baseline to ERCOT regional equivalent (e.g. Western Interconnect El Paso Electric).

• Gas demand for all other uses (Residential, Commercial, Industrial, and Vehicular) derived from EIA Gas Consumption Data, with a 3% demand growth assumption year-over-year.

Gas production, storage, and consumption were modeled zonally (rather than nodally), consistent with our Generation Model numerically with a regionally uniform supply and demand basis. Four supply and demand regions were identified, each comprising one or more operating gas basins in their entirety and with consumption centers wholly contained in the region:

• **West,** the boundary of which includes the western and northern state border and continues around to the intersection of the Red River with a curve approximating the Balcones Escarpment. Gas production in this region is from the Permian Basin, and the region's demand centers include El Paso, Midland/Odessa, Lubbock, and Amarillo.

• **Northeast,** the boundary of which follows the northern state border to its eastern extent and continues around the eastern border (Sabine River) until it reaches approximately 31 degrees north latitude and follows the 31 degrees line back to the Balcones Escarpment. Gas production in this region is from the Barnett and Haynesville Shale formations, and the region's demand centers include Dallas-Fort Worth, Waco, and Tyler.

• **Southeast,** the boundary of which follows the eastern border of the state southward from 31 degrees latitude until it reaches the Gulf of Mexico, then follows the coastline around to the northern extent of Matagorda Bay and then bears northwest toward San Marcos until it reaches the Balcones Escarpment. Gas production in this region is minimal, and the region's demand centers include Houston, Austin, Beaumont, and Bryan-College Station.

• **South,** the boundary of which follows the Rio Grande from the Balcones Escarpment until it reaches the Gulf of Mexico, then follows the coastline around to the northern extent of Matagorda Bay and then bears northwest toward San Marcos until it reaches the Balcones Escarpment. Gas production in this region is from the Eagle Ford Shale formation, and the region's demand centers include San Antonio, McAllen, Corpus Christi, and Laredo.

These regions are connected by intra- and interstate pipeline systems and one or more gas hubs facilitating transfer.

Appendix G

G.2 Scenario definition

The report analyses 3 different scenarios of extreme weather conditions. These include hot summers, cold winters, and extreme storms (hurricanes). In all the scenarios, supply, demand, and infrastructure are affected in different ways.

G.2.1 Heat wave

The adjustments for the heat wave have been made using historical data of extremely hot days in the past years. This scenario is simulated using August 2024 as a base case. No additional modifications to the general inputs described in Section G.1 were required for gas infrastructure in this case, therefore:

1. Production is unconstrained aside from a 3% year-over-year decline from 2021 levels.

2. Gas Storage deliverable volumes are unconstrained, equal to 2021 levels.

3. Major gas pipeline systems shutdown: Kinder Morgan Texas, Whistler, and Williams Transcontinental.

4. Gas demand for power generation as per Generation Modeling results.

5. Gas demand for other consumption equal to EIA 2021 levels, inflated at 3% year-over-year.

G.2.2 Cold wave

The adjustments for the cold wave have been made using historical data from the Winter Storm Uri that took place in February 2021 in North America.

This scenario is simulated using February 2024 as a base case. Additional modifications to the general inputs described in Section G.1 are as follows:

1. Production baselined at 3% year-over-year decline from 2021 levels, with 30% curtailment due to power loss and miscellaneous downstream infrastructure shutdowns

2. Gas Storage deliverable baseline equal to 2021 levels, with 30% curtailment due to power loss and miscellaneous downstream infrastructure shutdowns

3. Major gas pipeline systems shutdown: Kinder Morgan Texas, Whistler, and Williams Transcontinental

4. Gas demand for power generation as per Generation Modeling results (maximum simulated demand, with all natural gas power plants available)

5. Gas demand for residential consumption at 150% of baseline (EIA 2021 levels, inflated at 3% year-over-year), reflecting increased supplemental heating and increased use of whole-home natural gas generators

6. Gas demand for other consumption equal to EIA 2021 levels, inflated at 3% year-over-year

Appendix G

Further sensitivities were calculated for this scenario, envisioning a supply:

- fully relying on gas production (no gas storage deliverables)
- full relying on gas storage (no production)

These scenarios helped further delineate the regional necessities and priorities of both storage and production in the Cold Weather scenario.

G.2.3 Hurricane

The adjustments for the heat wave have been made using historical data of Hurricane Harvey that took place in Texas and Louisiana in August 2017.

This scenario is simulated using August 2024 as a base case. Additional modifications to the general inputs described in Section G.1 are as follows:

1. Production baselined at 3% year-over-year decline from 2021 levels, with 50% curtailment in Southeast and Northeast regions due to power loss and miscellaneous downstream infrastructure shutdowns.

2. Gas Storage deliverable baseline equal to 2021 levels, with 75% curtailment due to power loss and miscellaneous down-stream infrastructure shutdowns.

3. Major gas pipeline systems shutdown: Kinder Morgan Texas, Whistler, and Williams Transcontinental.

4. Shutdown of major Gulf Coast Pipeline systems and LNG Export facilities in South and Southeast regions, reducing net out-flow from South region from 5 bcf/d to 1.7 bcf/d and reducing net inflow to Southeast region from 0.9 Bcf/d to 0.1 bcf/d.

5. Gas demand for power generation as per Generation Modeling results.

6. Gas demand for other consumption equal to EIA 2021 levels, inflated at 3% year-over-year.

Appendix G

G.3 Results and Conclusions

G.3.1 Heat wave

A heat wave is not onerous for gas delivery. Production volumes remain consistent, demand does not differ significantly from baseline characteristics, and infrastructure are designed for hot temperatures. Local power curtailments due to increased electrical distribution load are not likely to have widespread effects on the Texas gas infrastructure's ability to meet demand.

G.3.2 Cold wave

A cold wave is much more onerous for gas delivery than a heat wave. Production and storage curtailments render both sources unable to satisfy demand on their own, necessitating a security of supply strategy which prioritizes gas storage delivery first and maintaining as much production as possible second. Pipeline curtailments require a greater extent of natural gas transfer within the state, but when state-wide net supply exceeds state-wide net demand, the pipeline system can deliver the required gas within regions.

This scenario highlights the **general** ability of the state's gas infrastructure to perform in a cold weather scenario, but it should not be interpreted as dismissing the importance of further investigation into the resilience of the various gas storage sites and the thousands of miles of gas distribution pipelines and laterals within each region. The fitness of these storage sites and pipelines will make the difference between a system which delivers when called upon and a system which fails to deliver.

Further, the scenario highlights the need for the state to ensure that gas storage sites are filled to working capacity prior to the onset of the winter storm season.

G.3.3 Hurricane

A hurricane of scale similar to Harvey, while devastating, is not particularly onerous to gas supply. In this scenario, production, and storage volumes from Northeast and West Texas are sufficient to make up for curtailments and pipeline shutdowns in South and Southeast Texas.

Appendix G

G.3.4 Summary Results

Region	Value	Hot	Hurricane	Cold Unconstrained	Cold without Storage	Cold without Production
Northeast	Net Supply	8,181	8,181	5,234	2,574	2,660
Northeast	Net Demand	3,226	3,226	4,691	4,691	4,691
Northeast	Supply Constraint	No	No	No	Global	Global
Northeast	Pipeline Constraint	N/A	N/A	N/A	No	No
Southeast	Net Supply	13,848	3,474	9,163	483	8,680
Southeast	Net Demand	4,792	4,792	5,632	5,632	5,632
Southeast	Supply Constraint	No	No	No	Global	Global
Southeast	Pipeline Constraint	N/A	N/A	No	No	No
South	Net Supply	841	1,221	(911)	(911)	-
South	Net Demand	760	760	1,274	1,274	1,274
South	Supply Constraint	No	No	Local	Global	Global
South	Pipeline Constraint	N/A	N/A	No	No	No
West	Net Supply	11,813	11,813	7,831	6,781	1,050
West	Net Demand	2,431	2,431	5,547	5,547	5,547
West	Supply Constraint	No	No	No	No	Yes
West	Pipeline Constraint	N/A	N/A	N/A	N/A	No
Total	Net Production	16,983	16,983	8,927	8,927	-
Total	Storage Deliverable	17,700	17,700	12,390	-	12,390
Total	Net Supply	34,683	34,683	21,317	8,927	12,390
Total	Net Demand	11,209	11,209	17,144	17,144	17,144

1) All values in MMscf/d