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# Fostering Resiliency with Good Market Design: Lessons from Texas

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# Fostering resiliency with good market design: Lessons from Texas

Peter Cramton[1]
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*Abstract*

In February 2021, winter storm Uri brought extreme cold to Texas for many days. The cold caused a spike in electricity and natural gas demand and simultaneously a sharp drop in supply. The electricity shortage caused 4.5 million Texans to lose power for multiple days. Many lost water service too. Storm damage was extensive, including many deaths. This paper examines what happened and offers solutions to improve the reliability and resilience of critical infrastructures. Improved communication before and during the storm would limit the damage. Natural gas market reforms would enhance the reliability of the gas supply, enabling more generators to produce power. Improved energy efficiency would limit the cold-induced demand spike. In addition to ongoing initiatives to integrate storage and distributed generation, the system operator should introduce a voluntary forward energy market that lets market participants better manage risk and plan resources to meet demand. Price-responsive demand should also be encouraged to limit demand surges in cold snaps.

## Introduction

During four frigid days in mid-February, the Texas electricity market had more demand than supply. Out of necessity, the Electric Reliability Council of Texas (ERCOT), which operates the system, requested controlled outages for roughly 20 percent of the system. Electricity, unlike other products, requires that supply and demand balance every second so that frequency and voltage stay within tight tolerances. Absent this balance, generating units will trip off, causing a catastrophic blackout.

The controlled, multiple-day outages that avoided such a total blackout in Texas nonetheless inflicted a severe human cost. Storm deaths total 246. Property damage is estimated at $130 billion. The event should not be repeated, not in Texas nor anywhere else.

The Texas crisis's proximate causes were two unanticipated shocks induced from the sub-zero temperatures (-2˚ F in Dallas): 1) a failure of conventional (thermal) generating supply, mostly from lack of natural gas, and 2) a surge in electricity demand.

Inadequate winterization caused freezing of the gas supply and many plants' control instruments. In a system with a winter peak of 66 gigawatts (GWs), about 30 GWs of thermal plants were unavailable. In its worst-case extreme-winter analysis, ERCOT had expected a loss of 14 GWs of thermal resources. The

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February storm caused more than double the anticipated thermal outages. Wind resources also experienced storm-related outages, but ERCOT anticipated these outages in its planning.

Simultaneously, electric heaters created a powerful surge in demand. About 61 percent of Texans rely on electric heat, mostly low-efficiency resistance heat, in poorly insulated homes—a seemingly sensible choice in a warm climate with cheap electricity, where home heating is often unnecessary. The demand surge caused by the cold came to about 20 GWs or one-third of the winter peak. ERCOT based its worst-case analysis on a 2011 winter storm, the most severe cold-weather event in Texas in twenty years. The 2021 storm was much worse than that of 2011. It created an unexpected and unsupportable demand surge.

The combination of a sudden drop in supply and a surge in demand made it impossible to balance the system without initiating controlled outages. On Monday, February 15, at 1:20 am, ERCOT control room operators instructed distribution companies to shed load. Over the four days, the shortage was as high as 20 GWs and averaged about 10 GWs or 20 percent of demand. The deficit was so large that most distribution companies could not rotate their outages due to inadequate control systems. Millions of Texans were without power and water for days during freezing temperatures.

From a consumer perspective, there are few products as boring as electricity. It is there when you need it. You pay your monthly bill—always about the same and seemingly out of your control. You rarely worry about electricity, aside from brief local interruptions such as a tree branch downing a line or a squirrel causing a short circuit. Electricity is considered dependable. Even during Hurricane Harvey, the Category 4 storm that struck Texas in 2017, ERCOT did not need to order power outages.

Behind the consumer's easy access to electricity is one of the most sophisticated markets in our modern economy. Experts have carefully designed electricity markets to provide reliable electricity at the lowest possible cost. The market can and should be improved.

As policymakers grapple with the events of February 2021, it is vital that the victims of this crisis—the Texas public—understand what happened and what prudent steps are needed to avoid such tragedies in the future. The sooner we know the elements involved, the sooner regulators can direct resources to deal with them. Preventing similar catastrophes will require a dedicated effort.

It is also essential that policymakers rely on independent expert analysis rather than the moment's talking points from interested parties. A market functions best when its rules evolve from basic principles. Such a market reduces risks to participants and therefore costs to consumers. Participants can manage market risks; political risks are unhedgeable.

As the world confronts climate change, our dependence on electricity must increase. Rapid innovation in the electricity sector brings challenges and opportunities for the electricity grid. At least for the next twenty years, as we rely more on renewable resources for our energy, we must rely even more on natural gas resources and price-responsive demand for our reliability and resilience.

The Texas crisis shows how critical infrastructures are vulnerable to failure when confronted with events that exceed the levels of stress for which they are designed.

Effective electricity market design is crucial as the market rapidly changes technologies in response to efforts to mitigate climate change. The task is challenging since it involves interdependent electricity and natural gas systems. Making effective adjustments is essential not only in Texas but worldwide.

## What happened?

Like other electricity systems in the United States, the Texas grid is a centralized and highly regulated market. A high degree of regulation and central control is required to balance supply and demand second by second and simultaneously to satisfy thousands of resource and grid constraints. "Deregulated" is a poor term to describe the market. Texas has a *restructured market* that replaces a single producer of electricity which charges administratively set tariffs with a competitive market for generation and retail choice. This structure has reduced consumer costs and improved reliability. With either approach, system-wide outages are rare. The last multi-day, large-system outage in the United States was the 2003 Northeast blackout caused by inadequate tree trimming near transmission lines and a software bug in the transmission owner's control system.

A fundamental purpose of electricity markets is to balance supply and demand every second in the most economic way. The system operator achieves balance through a conceptually simple pricing mechanism: the decentralized decisions of thousands of market participants in a transparent, fair, and efficient process described precisely in the market rules. All the restructured markets work in this way, from New England to California.

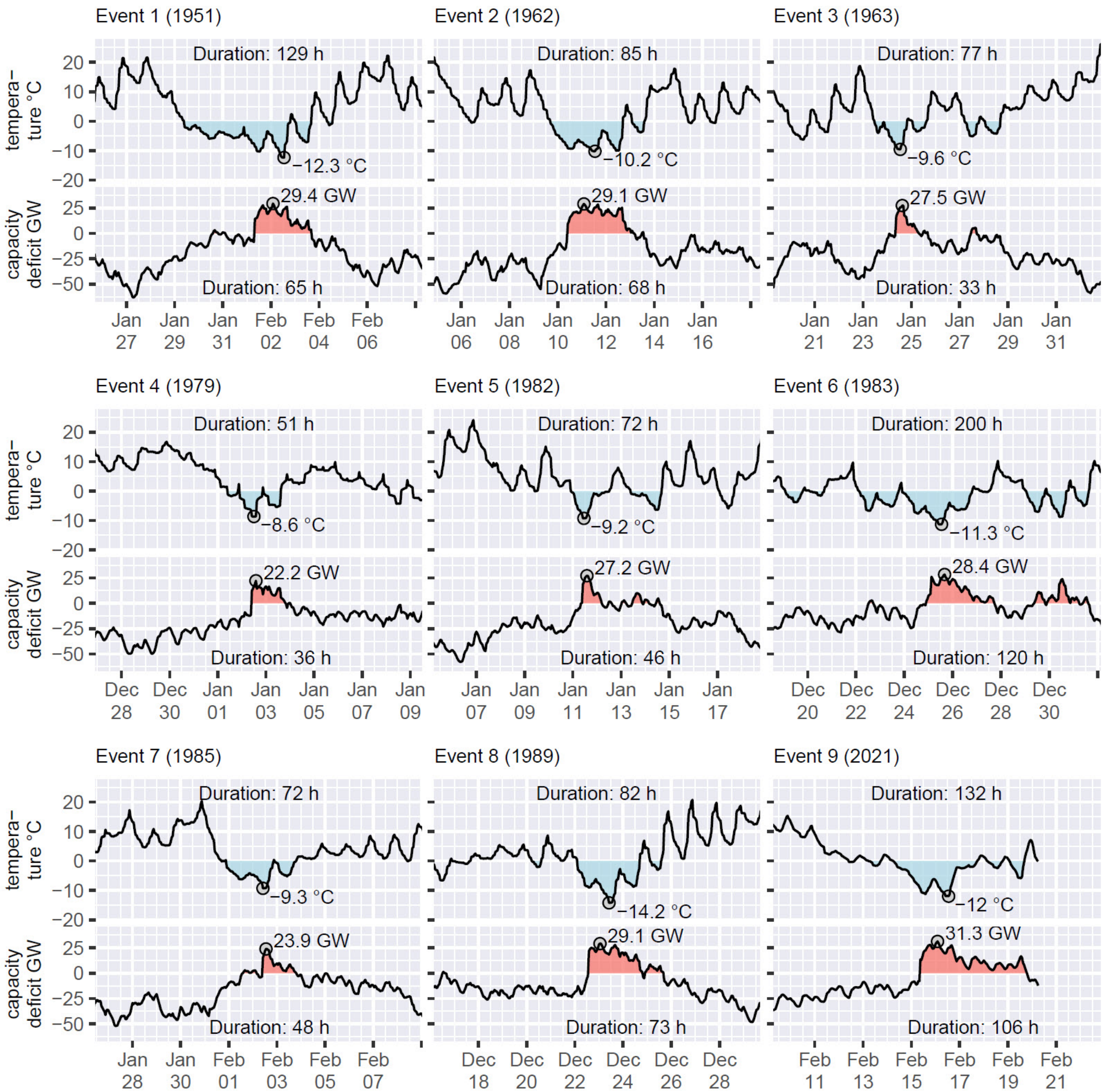
ERCOT performs detailed studies in advance of the winter and summer peaks to determine if the ERCOT market has sufficient resources to satisfy demand in a modeled worst-case event. ERCOT based the worst-case extreme-winter analysis for 2021 on the 2011 storm.

The analysis, consistent with current practice in the industry, does not include systemic failure. The study evaluates *resource adequacy,* assuming the expected quantity of forced outages, not a dramatically higher rate of outages from correlated collapse. Thus, ERCOT's assurance that the market could weather the storm of winter 2011 was correct. But the methodology needs to be improved to consider more extreme events and the potential of correlated failures. Improving the approach is on ERCOT's to-do list and probably on the to-do lists of regulators and system operators elsewhere—each system learns from events elsewhere.

Unfortunately, the February 2021 storm was much worse than the 2011 storm. Temperatures were substantially lower throughout Texas in 2021 and continued for longer. Dallas had a low of 13˚ F in 2011 vs. -2˚ F in 2021. Austin had 69 consecutive hours below freezing in 2011 vs. 162 in 2021. The 2011 storm caused 7.5 hours of load shed of up to 4 GWs. By contrast, the 2021 storm caused 70.5 hours of load shed of up to 20 GWs. Every dimension of the 2021 storm was worse.

Gruber et al. (2021) examines the worst cold snaps in Texas history from 1950 to 2021. The 2011 crisis does not make the list. Below is the temperature and electricity demand for the nine worst cold-snaps with each year scaled to 2021 for comparability. Temperatures below freezing are shown in blue and electricity shortages are shown in red. 2021 is among the worst, although several other years are comparable: 1962, 1983, and 1989.

*Relationship between cold temperature and electricity shortage during Texas cold snaps, 1950-2021 (Source: Gruber et al. 2021)*

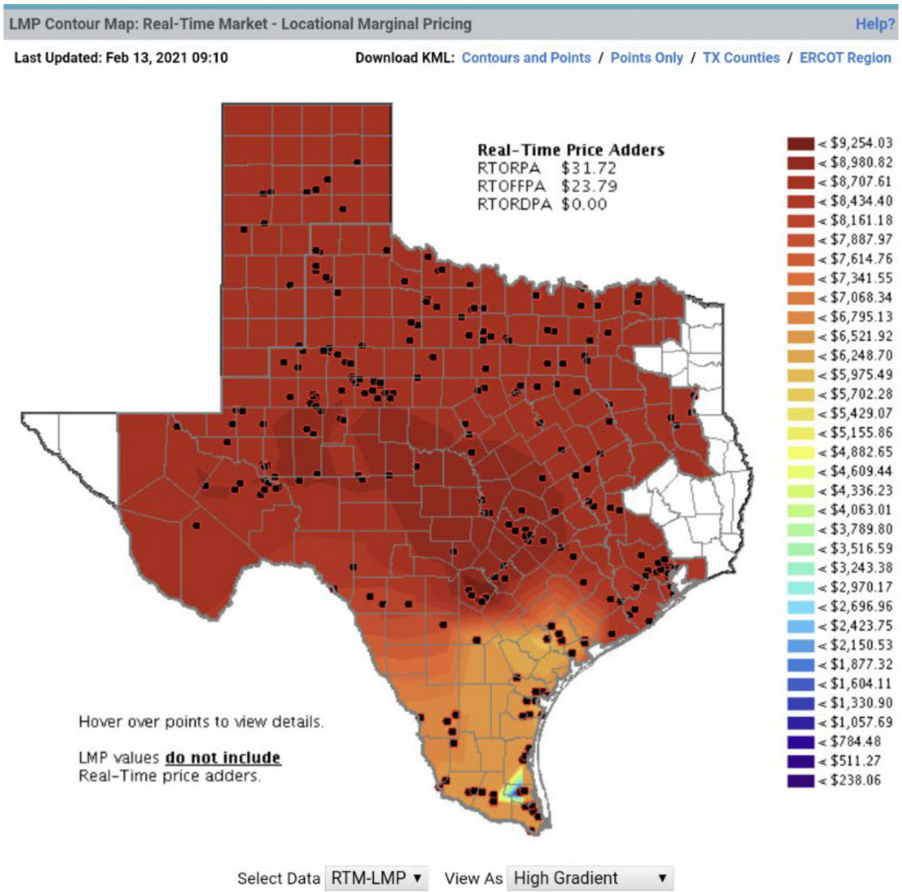



To understand what happened, I first consider events from a market participant's viewpoint. Weather is key to understanding electricity demand. Weather is also central to understanding production from renewable sources. ERCOT gets multiple weather forecasts. Some look far ahead, some are seasonal, and some are close to real-time. ERCOT aggregates the studies into a publicly available load-and-supply forecast that it updates continuously.

The market participants were well-informed about the severity of the upcoming 2021 storm from these forecasts and their own analyses.

On February 8, more than five days before the crisis, the ERCOT board met. Bill Magness, the CEO, opened the meeting, emphasizing that a massive storm was on the way. Market participants should stand ready. By the morning of February 13, it was clear that the storm would cause trouble. Real-time prices at 9 am CT were briefly near the $9000 per megawatt-hour (MWh) cap in most of Texas.

*Real-time prices in Texas at 9:10 am February 13 (Source: [ERCOT] on February 13, 2021)*




Texas generators' incentive to perform comes from one essential number, $9000/MWh, an administrative shortage price set by the Texas Public Utility Commission (PUC). It represents the value of lost load or, equivalently, the load shedding cost per megawatt-hour basis. It is needed because demand response to high prices is sometimes too limited to balance the market. In normal times, the system operator can balance the system with a higher price. During an emergency, attempts to balance with price alone are insufficient. ERCOT must shed load, and the economic cost per unit of energy is $9000/MWh.

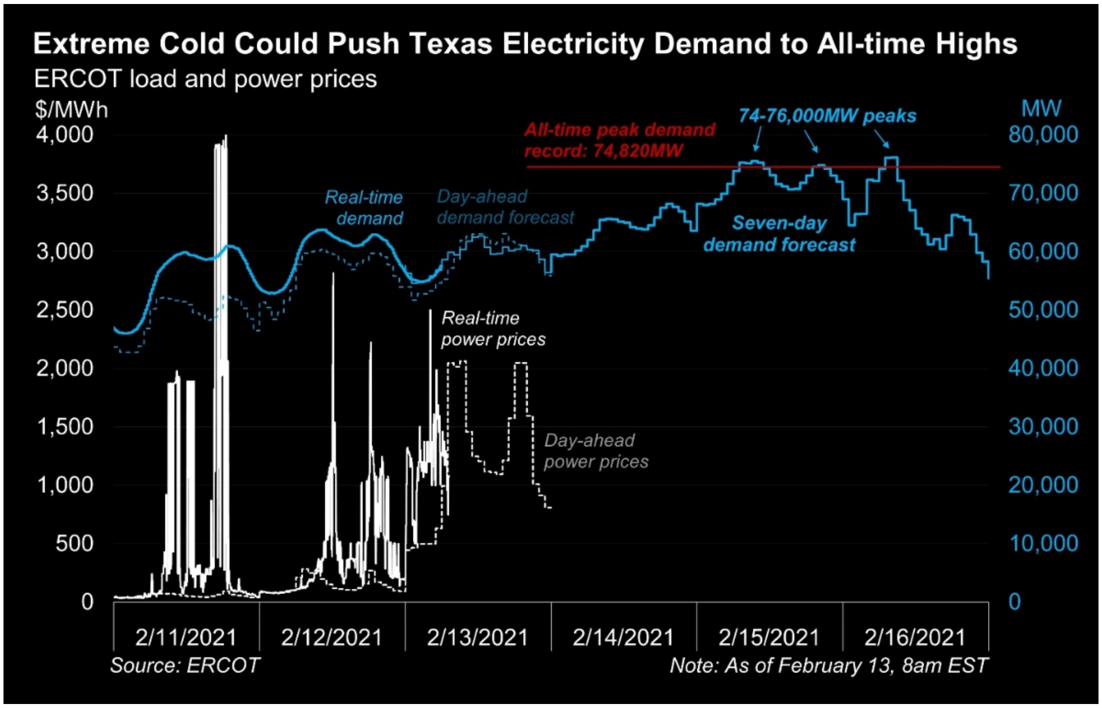
To get a sense of the magnitude of the incentive, consider a supplier with a 1000 MW natural gas plant. If the generator had effective winterization during the February crisis and had natural gas available, it would receive $9000/MWh to generate at its upper limit. The crisis lasted 4 × 24 + 7 = 103 hours. Thus, its total payment is $9000/MWh × 1000MW × 103 = $927 million. This same logic applies if the generator had sold forward its energy, as is common to manage risk better. The generator would be on the hook to deliver the energy, and the contract would require that any shortfall is settled at the real-time price of $9000/MWh. Thus, not delivering involves a penalty of $927 million or the loss of a reward of $927 million, depending on whether the generator had sold forward.

A payment of $927 million for supplying energy for 103 hours would seem to provide a strong incentive to perform. This amount is roughly equal to a new 1 GW combined cycle plant's entire capital cost. No market has stronger performance incentives. For comparison, the total capital cost for a 1 GW combined-cycle natural gas plant is $958 million, according to the EIA. The lifespan of such a plant is 40 years. Thus, the performance incentive was enough to cover the unit's total capital cost.

An energy analyst, Brian Bartholomew, was following the crisis like thousands of market participants. He posted a series of charts that tell the unfolding story. The charts are from ERCOT's publicly available real-time information.

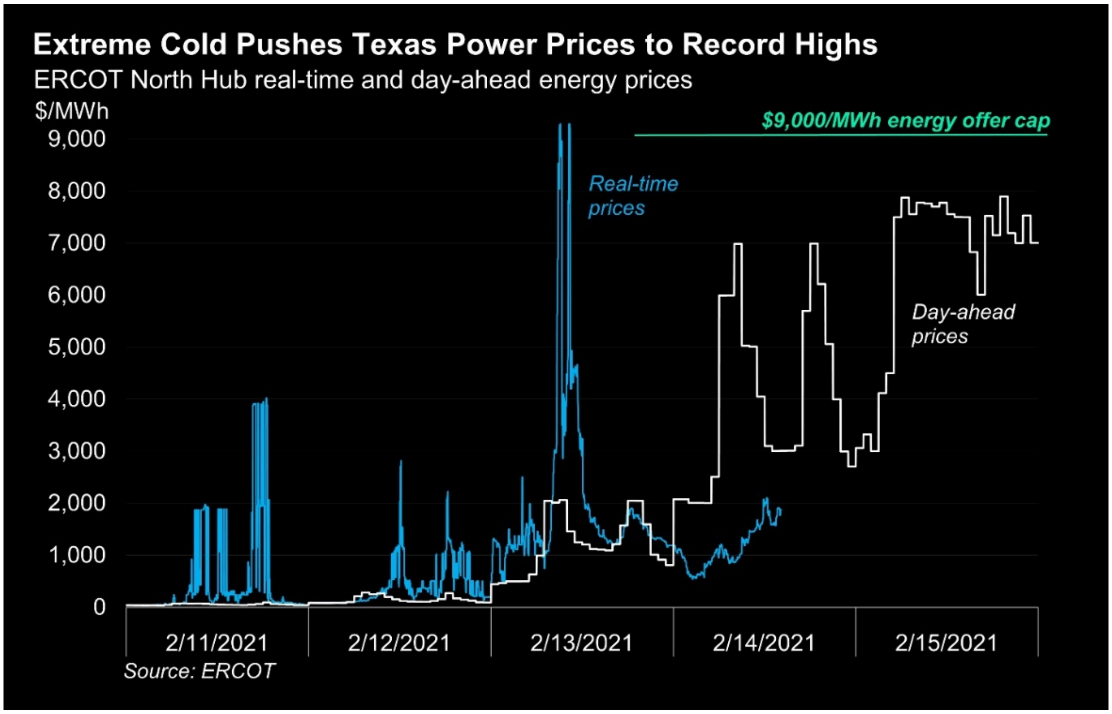
The first chart shows the situation at 7 am CT on Saturday, February 13. Prices are more than 100 times normal many times over the prior two days. Day-ahead prices were about 100 times normal for the rest of the day. The most concerning was that the seven-day forecast was a nightmare—demand was forecast to shatter the winter peak record of 66 GWs and break the summer peak of 76 GWs. All market participants see this information at 7 am CT on Saturday. It was sure to be an extreme event with sustained prices at the cap of $9000. Every generator was doing everything it could to generate power in such an environment. The incentive to perform throughout the storm was exceptional. Similarly, every industrial customer faced the same $9000 incentive to shut down or reduce operations. Every service provider was motivated to reach out to customers via email, text, and phone to urge them to prepare for the storm and limit their electricity use.

*Load and power prices, actual and forecast at 7 am CT, February 13 (Source: Brian Bartholomew)*



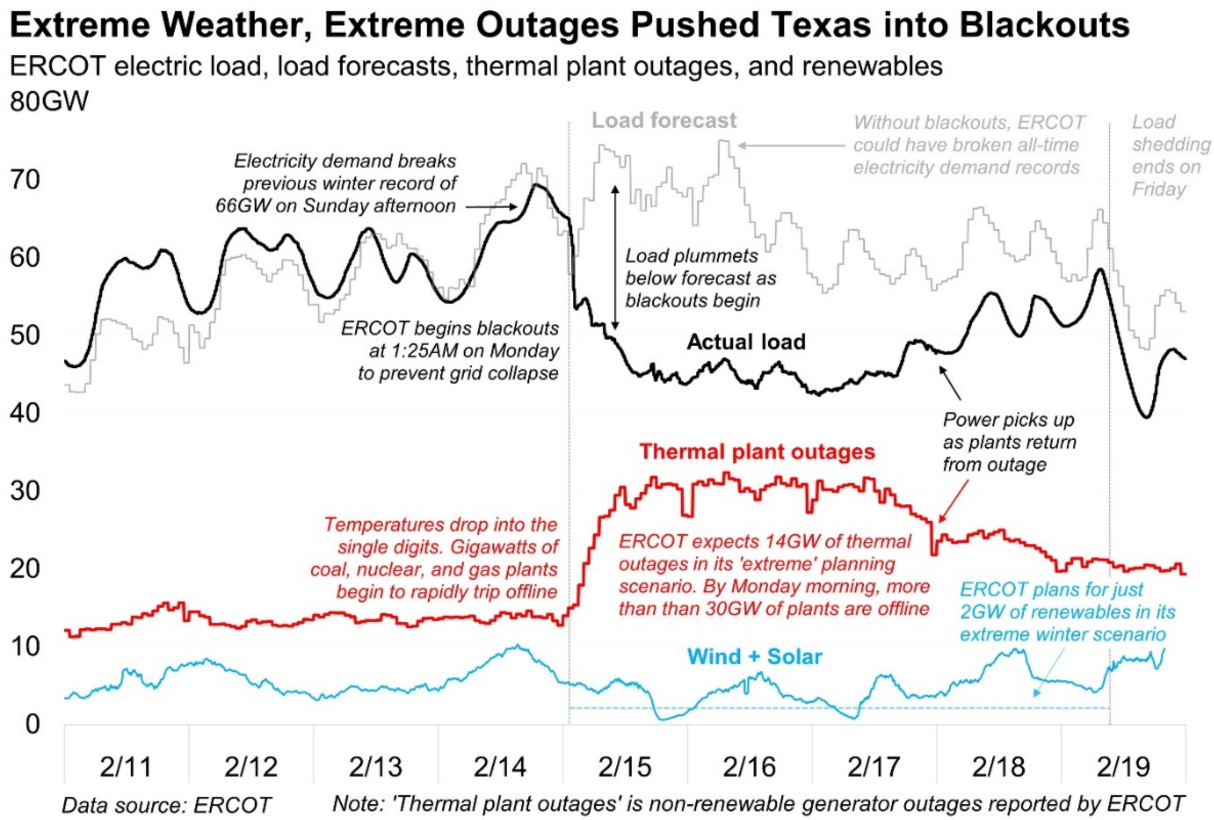

Thirty-one hours later, at 2 pm CT, the market had experienced many periods with prices at the cap over the prior day. Day-ahead prices for the current day, February 2021, were about $7000 for two hours, and there were sustained periods above $7000 the next day. The situation was extreme.

*As of 2 pm CT, February 13, real-time prices reach the price cap, and day-ahead prices are near the cap (Source: [Brian Bartholomew](Brian Bartholomew))*




Unfortunately, events only got worse. The final chart shows the load leading up to the event and then the load forecast and actual load throughout the crisis. At the start of the crisis on Monday at 1 am CT, February 15, demand (load forecast) spiked upward as outages from thermal plants also spiked, making it impossible for the system operator to balance supply and demand. Load had to be shed, resulting in sustained blackouts for over four million Texans during the cold.

*Load forecast, actual load, thermal plant outages, and renewable production, February 11-19, 2021 (Source: Brian Bartholomew)*

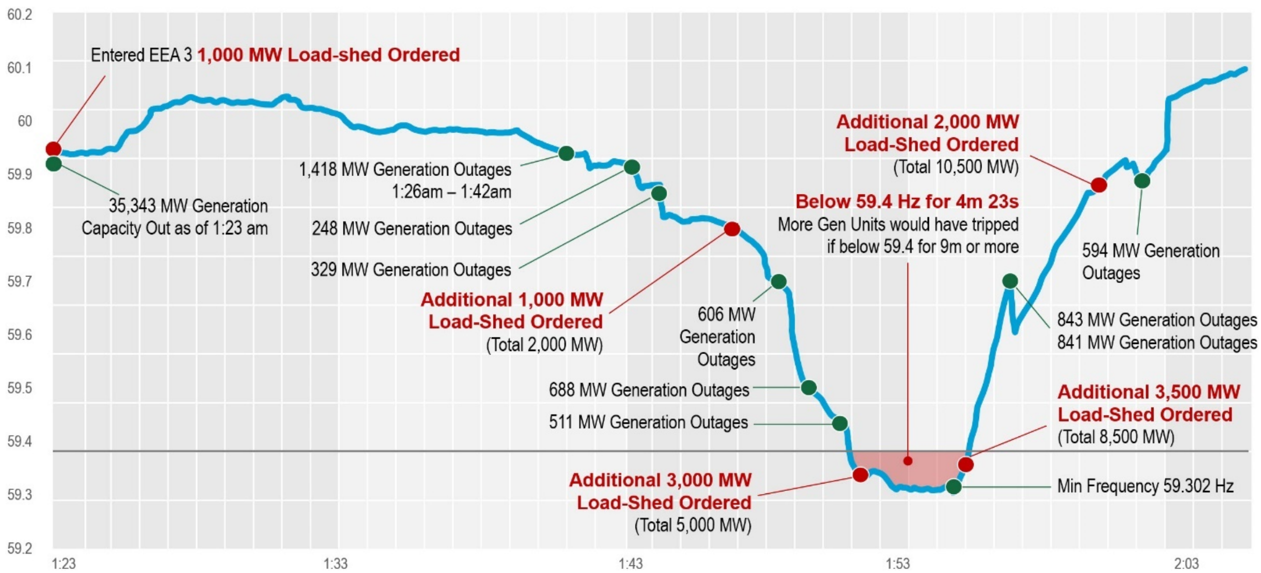



The chart also shows wind and solar performance before and during the crisis. One can see the drop in renewable production heading into Sunday night, February 14. But the decline was modest compared to the spike in thermal plant outages in the early hours of Monday, February 15. There were only two brief instances throughout the crisis when renewable production was below the extreme winter benchmark. Relative to expectations, renewables overperformed, and thermal plants underperformed during the crisis. The dramatic underperformance of thermal plants—coal, natural gas, and nuclear—reached 16 GWs below the extreme winter scenario.

The spike in thermal outages was only part of the problem. The other part was the sharp increase in demand, about 10 GWs higher than predicted in the extreme winter scenario. This spike in demand was attributable to about 35 GWs in heating load.

Our second viewpoint is that of an operator in the ERCOT control room. The system operator initiated Energy Emergency Alert 3 (EEA 3) at 1:23 am on Monday, February 15, when ERCOT ordered the first gigawatt of rotating outages. Eighteen minutes later, a series of outages began causing a significant drop in electrical frequency. ERCOT must hold the frequency nearly constant at 60 cycles per second (Hz) or units trip off. At 1:51 am, the frequency fell below 59.4 Hz and was crashing lower—below 59.3 Hz additional units would trip. The situation was urgent. ERCOT ordered a large 3GW load shed, stopping the frequency drop, but it remained below 59.4 Hz. Other units would trip if the frequency remained below 59.4 Hz for four more minutes. ERCOT ordered a large 3.5GW load shed. This demand reduction finally got the frequency to increase. ERCOT called an additional 2 GW reduction to bring the system back to 60 Hz. The total controlled outage was 10.5 GWs.

*A rapid decrease in generation causes frequency to drop, requiring controlled outages (Source: [ERCOT](ERCOT))*




Although the operators got the system back to 60 Hz within minutes, the emergency was far from over. Over the next four days, the operators had to maintain the damaged system's balance. Downed units would struggle to come back. More units would fail. The quality of the reserves was questionable. At my final board meeting on February 24, I put it like this, "ERCOT was flying a 747. It had not one but two engines experience catastrophic failure. [ERCOT] then flew the damaged plane for 103 hours before safely landing in the Hudson. In my mind, the men and women in the ERCOT control room are heroes." I still believe this.

The system was minutes away from a complete blackout. Had this happened, the human tragedy would have been orders of magnitude worse. Unlike the systems to the West or East, which can jump-start their production using the Hoover Dam, Niagara Falls, or Direct Current ties of neighboring grids, Texas has no such option. "Black start" in Texas would be a delicate and lengthy process that would have to start from zero. It would take many weeks to execute. During that period, aside from what first responders could truck in or airlift from neighboring states, there would be no electricity, no heat, no water, no gasoline, and no standard communications.

Based on what happened, I consider what regulators should do to reduce the chances of another crisis and to lessen the harm if it does.

## Improve communications

ERCOT, the PUC, the Governor's office, and thousands of market participants knew of the terrible storm days in advance. As it grew closer, the magnitude of the crisis became apparent. By Friday, February 12, it appeared likely that load-shedding would be required. By Saturday, February 13, significant load shedding was expected. On Monday at 2 am CT, it was known that there would be load shedding on the order of 10 GWs for many days.

ERCOT's job is to give days-in-advance (seven-day) forecasts to market participants, update the forecasts constantly, and provide both day-ahead and real-time market information. ERCOT publicly posts and continuously updates this information. As the possibility of an emergency nears, ERCOT informs its board, the PUC, and the Governor's office. ERCOT did all this throughout the crisis. Its systems faithfully implemented the market rules, including the delivery of information.

Despite this, communications with the public were inadequate. The immediate question is who should be in charge of communications to the public and how should communications be made. One thing is clear: people would have benefited enormously from clear communications on what to do in advance of and during the winter outage: stay off the roads; fill your bathtubs with water (to ensure that water is available); fill most buckets or pitchers with water and set them outside (to put the resulting ice blocks in your refrigerator to keep food cold). Save at least one bucket or pitcher to transport water from the tub. Find your water main, and before any freezing begins, shut it off. To remove the water currently in the pipes that may freeze and damage your pipes, start at the top of the house, open every faucet, and flush every toilet. Find your warm clothes and bring them to a core area in your home. Make sure that phones, tablets, and computers are fully charged. Locate flashlights, batteries, and other survival equipment.

Many Texans are not used to sustained freezing temperatures. A public service message would have been helpful to many. Who should make such a message? A responsibility of political leaders is effective communication with the public during crises. Warnings should have sent on Friday, Saturday, and Sunday before the storm. The statements may cause panic. That is why political leaders, who are suited to maintaining calm during a crisis, are best able to send the message.

During the crisis, political leadership needed to send a second important communication: "It is likely that many Texans will lose power because of the storm, some for multiple days. The number of Texans who must experience a long outage in freezing temperatures depends on your actions. I ask and plead with all Texans who have power: *Please put your sweaters and coats on and turn the thermostat down to 55˚ F or lower*. Each kilowatt-hour you conserve enables more Texans to have power. Let's stand together and defeat this storm."

A third important message would have dealt with the use of natural gas: "If you have a gas fireplace, do not use it. Your fireplace is not designed for heating. That gas is needed to power the state's generators. In many cases, gas fireplaces are to display a flame, not warm your room. Please let our highly efficient generators have that precious gas. Your use of the gas fireplace is robbing Texans of heat and electricity." I saw TV segments of families huddled around gas fireplaces during the bitter cold. The instinct to use the gas fireplace was natural but increased the overall suffering. By contrast, wood-burning stove is an excellent example of resilient heating during a winter outage.

*Resilient heating in winter*

A fourth matter that required communication was an important safety message. "Many Texans will die from operating a vehicle or a generator in a garage. Do not be one of them. Do not operate a vehicle or a generator in a garage. Even if the garage door is open, the ventilation is insufficient to prevent death from carbon-monoxide poisoning."

In addition to media outlets, Amber-type emergency communications could broadcast these messages. Post-crisis, every American should be urged to prepare an emergency kit that includes the essentials to survive without electricity or water for 72 hours.

Another important channel of communication to retail customers is their service providers. Each service provider can reach its customers via phone, text, and email. A good example of this communication is Griddy, a small provider with an innovative pricing model. On February 11, Griddy had about 29,000 customers. Each had a simple electricity plan, $10/month plus wholesale cost, which averaged under 9 cents per kilowatt-hour—less than 3 cents for energy and 6 cents for the fixed cost of distribution and transmission. The Griddy plan passes the wholesale cost to customers without any markup. Griddy realized the storm's magnitude and understood its impact on Griddy customers. Exposure to real-time prices meant high bills during the storm.

On Friday, February 12, three days before the crisis, Griddy contacted its customers via phone, text, and email with a simple message: please switch to another provider that can offer you a fixed-rate plan. Griddy knew its customers' would be best-off changing retail plans before the crisis. Switching would also benefit Griddy since many customers would be unable to pay their bills, and Griddy would be responsible for the liability. Griddy successfully got about 10,000 of its customers, more than one-third, to switch plans before the crisis started.

This clear and effective communication did not prevent subsequent media stories noting $17,000 bills and the supposed price gouging of its customers by Griddy (CBS7). Griddy was not price-gouging. They passed on the wholesale cost, the PUC-set price of $9 per kilowatt-hour. At $9, a $17,000 bill would imply consumption of 1889 kWh during the four-day crisis or 472 kilowatt-hours per day—twelve times the average Texan household's consumption. The absurdity of the matter extends to an announced lawsuit against Griddy by the State Attorney General for charging customers the PUC-set electricity price without any markup.

Griddy and a rival, Octopus Energy, a company that also offers the wholesale-cost plan, both recognized months ago that the problem with their retail plan was that it did not include a price-hedge to protect consumers during shortage events. I reached out to both companies in October 2020 and urged them to add a plan with an automatic price hedge. Both companies were hard at work on establishing such hedged plans. The challenge was coming up with a plan that retail consumers would understand. Both Griddy and Octopus Energy were about to introduce innovative price-hedging rate plans later in the winter.

Shortly before the storm, Octopus introduced a fixed-rate plan. It actively encouraged its customers to switch to the fixed-rate plan both before and during the storm. On February 22, Octopus, having many fewer customers than its more senior rival, decided to absorb nearly all the wholesale costs its customers incurred during the crisis. Octopus charged just 12.2 cents yet paid 900 cents per kilowatt-hour to the electricity wholesale market. Following the storm, Octopus reached out to its customers via phone and text to know how they were doing.

The communications of both Griddy and Octopus were exemplary.

The nice thing about improving communications is it can be done immediately, at virtually no cost. Its benefit is immense—especially in preventing loss of life and property damage.

## Improve critical infrastructures essential for a resilient grid

The following two steps on this list are of vital importance. Both will take time and money. Both require a dedicated effort by regulators and the legislature. The first addresses the main supply problem; the second addresses the main demand problem.

### *Reform the natural gas market to assure a reliable supply of gas in sub-zero temperatures*

Many pointed to frozen windmills in Texas as a key reason for the February electricity shortage. Yes, many wind turbines had to go offline because of excessive ice on their blades. But this loss was minor compared with the failure of conventional resources—gas-, coal-, and nuclear-powered production.

In the first hours of Monday, February 15, units of every type went offline. Wind lost about 3 GWs in the early hours of Monday. The largest loss was from natural-gas production, which declined by about 15 GWs. Coal and nuclear energy sources also had losses. Wind performed better than expected in all but a few hours during the storm. It was not these few hours of modest underperformance that caused ERCOT to shed large amounts of load.

As we add more renewables, we must rely even more on natural gas to provide energy during shortages, at least until there is an economic alternative for long-duration storage. The 31 GWs of wind nameplate capacity is only expected to produce about 1 GW in a winter storm. Even with expensive de-icing, that number is about 3 GWs. Therefore, a major concern is the poor performance of natural gas during the crisis. Preliminary evidence suggests that many gas units failed because of a lack of gas or inadequate gas pressure. Gas supply was a problem. Texas natural gas production dropped 45 percent when gas demand surged because of the extreme cold. Detailed forensic work will uncover to what extent the shortage was from lack of gas or gas pressure versus freezing at the generator. The distinction is essential. Texas can spend billions winterizing its gas-generation fleet. The grid will remain vulnerable to winter storms unless the gas supply is also winterized.

The gas market and the electricity market are interdependent. This relationship needs to be reflected in the regulation of both markets. The electricity market is built from the ground up to handle large supply and demand changes. In electricity, balancing supply and demand every second is essential. By contrast, gas is storable and controllable in ways that allow a much simpler market model.

We have learned that the Texas natural gas infrastructure is not up to the challenge of an extreme winter event. One cannot lose 45 percent of supply at a time of surging demand. This must change. For at least the next twenty years, natural gas will be the primary fuel for electricity during sustained shortages. The electricity grid's resiliency can be no better than that of the natural gas supply. It will be critical for gas suppliers to face the same strong performance incentives as electricity suppliers. Suppose a generating company purchases firm gas to complete its physical hedge to supply electricity. The gas supplier cannot hide behind a force majeure clause if it cannot deliver gas because of frozen gas lines or low pressure. (The gas does not actually freeze. It is hydrates that freeze into balls of ice that can restrict flow in a pipeline. The hydrates are formed when water vapor combines with hydrocarbons.) Strong performance incentives mean no excuses.

Gas prices did increase by a factor of about 100 during the crisis. Nonetheless, the gas market had a major shortage. There was a failure to deliver at any price. And many who bought gas forward and did not receive it were given a force majeure excuse rather than compensation for the failed delivery.

### *Use standards and grants to promote energy efficiency in new and existing homes*

Texas ranks 37th out of 48 continental states in energy efficiency. A low ranking should not be surprising, as gasoline and electricity are cheap in Texas. Gas and electricity prices are the primary drivers for consumers' to invest in energy efficiency. In normal times, this incentive is correct, and consumers can make the right choice.

But for energy efficiency in home construction, there is a severe market failure. Builders want cheap homes to sell more homes; energy companies want low efficiency to sell more energy. Consumers focus on home prices. They are less aware of energy efficiency. Public policy requiring consumer information about energy efficiency and efficiency standards corrects this failure. No one, absent information, would pay more for an energy-efficient home.

The regulator of home construction, the Texas Department of Licensing and Regulation, needs to work with the PUC to establish construction standards that support a resilient electricity grid. Installing inefficient resistant heat in most Texas homes makes resilience expensive for Texans. This expense is an externality not borne by the home buyer. It is a market failure that needs to be corrected. The critical infrastructures of electricity and shelter are interrelated. Some coordination is essential. Insulation and triple-pane glass are effective at improving resilience to extreme temperatures.

While better standards can address new construction, grants need to be used to subsidize energy efficiency improvements in existing homes. These grants should target the most effective means of improving efficiency—caulking and insulation. The grants should target those hit hardest by the crisis and those most influenced by support—those with less income.

This market failure is nationwide. The response should be a federal program implemented with matching funds from the state.

## Enhance oversight of ERCOT as the electric industry undergoes rapid innovation

### *Retain the core elements of the existing governance structure*

The board provides first-level oversight of ERCOT management. It is a crucial component of ERCOT's governance structure. The ERCOT board has an unusual structure. Most system operators have independent boards—members are independent of any stakeholders. ERCOT instead has a hybrid board. Eight board members are affiliated with stakeholder groups—four on the supply side and four on the demand side. The four-four structure balances the interests of the producers who want high prices with consumers who want low prices. Both sides of the market want reliable electricity. Then there are five independent board members with no association with any Texas market stakeholders. The bylaws require the board leadership positions—chair, vice-chair, and committee chairs—to be filled by independent directors. Finally, the PUC chair and the ERCOT CEO serve on the board. A desire for a reliable and resilient grid unites ERCOT management, board members, and commissioners. The broader mission of ERCOT and its board is "to serve the public by ensuring a reliable grid, efficient electricity markets, open access, and retail choice."

In my half-decade on the ERCOT board, I have found this hybrid structure to work well. The balanced representation of stakeholders gives the independent directors direct access to the various stakeholders' views and knowledge. For the most part, the board has operated on a consensus basis. An effective stakeholder process developed improvements as needed. The rule changes would come to the board, where, in all but exceptional cases, the support for the changes was unanimous. This process was faster and more effective than the stakeholder processes I observed in other US electricity markets. A good example is the slow introduction of essential performance incentives in East Coast capacity markets (see this electricity market design paper).

Stakeholder groups elect affiliated directors. By contrast, the entire board nominates independent directors. The bylaws give Texans preference, but being a Texan is not a requirement. There is a good reason for this. Electricity markets are complex and require specialized knowledge. Although Texas has many people with the necessary expertise in electricity markets, most of these experts are associated with one or more stakeholder groups and would not be independent. As a result, most independent directors reside outside of Texas.

### *Improve oversight to be more responsive to rapid innovation*

Both the PUC and the ERCOT board can benefit from streamlining oversight in recognition that the energy landscape is changing rapidly. Market rules and supporting systems need to be more responsive to this rapid technological change. ERCOT management and its board have understood this, but improvements are still possible.

The PUC can benefit from how the best communications regulators deal with rapid innovation in communications. At its worst, regulatory oversight maintains the status quo to limit competition for incumbents' benefit. At its best, it defines guiding principles and supports market rules that encourage competition and innovation for a vibrant industry. The PUC is closer to the latter, but further efforts in this direction are warranted.

## Improve ERCOT market rules and systems to embrace the future

There are many areas for improvement at ERCOT. These issues are frequently discussed by ERCOT and its board and indeed are the focus of ongoing key initiatives at ERCOT and among system operators worldwide. The pace of innovation in the core ERCOT system is limited by its necessary complexity and the need for exceptionally high performance levels. Even under extreme stress—massive hurricanes, prolonged heatwaves, and sustained cold—the system cannot fail. Those without power during the February storm rightfully view the blackout as a failure. But the ERCOT system did not fail; instead, the Texas market was unable to deliver electricity to over four million for multiple freezing days. This is terrible. But a system failure that results in a multi-day blackout of 24 million would be horrific.

### *Improve forecasting*

Improved forecasting is vital to electricity markets worldwide. As the share of intermittent renewables grows, so does the volatility of the net load that the system operator must manage with dispatchable resources. Fortunately, our forecasting ability is improving rapidly with enhanced models, measurement, and computation systems. Every system operator needs to take advantage of these improvements. One policy that would help is to create incentives for the public sharing of real-time weather information so that forecasting models can use more detailed information. Such information is collected privately at wind and solar farms. Forecasts from competing vendors should be made public to strengthen incentives for improved forecasts. Vendor performance is easy to assess from observed realizations.

### *Improve the analysis of resilience and reliability*

Electricity markets face two new forces, suggesting that more focus on resilience and reliability is desirable.

The first force is the energy transition. The electricity industry faces an unprecedented rate of innovation from new technologies on both the supply and demand sides. Intermittent renewable resources tend to increase net load variation, making it more difficult to balance supply and demand every second. Battery storage, electric vehicles, and smart thermostats are entering the market. These technologies help by fostering price-responsive demand. Still, it is challenging for market rules and systems to keep up with this rapid innovation.

An approximate equilibrium model of the energy transition in PJM is here. For decarbonization paths, see the Princeton report and Griffith handbook. Bill Gates' recent climate book emphasizes the importance of innovation on both the supply and demand sides. My colleagues and I explain carbon pricing's essential role in a rapid energy transition. The National Academies examines the energy transition challenges for future power markets.

The second force is climate change. Extreme weather events are becoming both more frequent and more extreme (Cohen 2021). The current approach of making decisions based on previous worst-case events, such as the 2011 Texas storm, is no longer adequate. New forecasting methods and modeling of extreme events are needed using a forward-looking methodology. Moreover, just as it makes sense to plan and train for a black start in the event of a total system collapse, it makes sense to prepare for systemic failures that cause long-duration shortages. Then the market can better limit the damage of such shortage events. For example, infrastructure can better accommodate higher levels of rolling outages. Better modeling of systemic failures will allow the regulator to identify the most significant vulnerabilities and seek ways of reducing the possibilities and costs of systemic failures.

### *Encourage price-responsive demand*

The long-term solution for both reliability and resilience is price-responsive demand. The critical market failure in today's electricity markets is the absence of demand response. Most consumers neither see nor feel real-time prices. Nonetheless, real-time prices reflect the social costs of consuming electricity.

The best designs, such as the Texas model, mitigate this failure with a shortage price set by the Public Utility Commission. It is $9000/MWh in Texas, roughly 300 times the typical electricity price. This high price motivates generators' long- and short-term decisions to improve reliability by providing energy during shortages. Consumers who see and feel the real-time price, primarily industrial users, are motivated to take action to consume less. Retail rate design needs to encourage more consumers to see and feel the real-time price while simultaneously protecting them from price risk. With enough demand response, prices would never reach the shortage price, and the system would be fully reliable.

Exposing a retail consumer to real-time prices increases consumer risk. But this risk is readily managed with a retail product that buys the consumer's expected consumption plus a safety margin on a forward basis, say monthly. The safety margin reflects that scarcity events tend to happen when demand is unusually high. Then the consumer sees and feels the real-time price on the margin, which is a necessary condition for economic efficiency. Still, most of the consumer's consumption is purchased by the retail plan at stable forward prices rather than more volatile real-time prices. When scarcity events occur, the consumer is alerted and can decide how much to reduce the thermostat to save potentially hundreds of dollars. In this way, the scarcity event turns from a scary additional cost to an opportunity to save hundreds of dollars. With vehicle-to-grid charging, a consumer with an electric vehicle will be able to do much more to improve grid reliability—charging the car when the price is low and discharging it to the grid when the price is high. This price arbitrage will reduce ownership cost, spurring electric vehicle adoption and further promoting price-responsive demand.

### *Integrate battery storage*

Battery storage is an essential complement to wind and solar power generation. The stored energy can smooth out at least some variation in renewable production. System operators today do not yet accommodate storage as seamlessly as is possible. Electricity markets should fully integrate storage of all forms. With full integration, storage resources offer their characteristics—charge/discharge rates, efficiency, and min/max states—and then their use for energy and reserves is optimized throughout the day. In this way, the system can maximize the value of storage resources.

### *Accommodate distributed generation*

Distributed generation is another resource that needs to be integrated into the market. The most common form of distributed generation is rooftop solar, but all distributed generation should be fully integrated. Doing so will increase reliability and resilience. For example, consider a home with both rooftop solar and battery storage. Even during a long-duration outage, such a home can maintain at least a minimum power level throughout the event—perhaps enough to keep all computer and communications devices going, the refrigerator, and enough heat to keep the pipes from freezing. This combination of solar + battery can be a powerful means of improving reliability and resilience, not just for those with the technology but for others. The February crisis will motivate many Texans to invest in solar + battery home installations. Both the state and ERCOT can help support these investments that bring reliability both from system-wide outages and from the more typical distribution outages caused by such events as hurricanes. Such private investments often reduce outage costs for neighbors, as solar + battery homeowners may let friends and neighbors recharge phones and other essential equipment.

### *Add a winter circuit breaker*

Financial markets typically have a circuit breaker that pauses the market when prices change too quickly. The circuit breaker stops algorithmic trading until humans can intervene to determine why the price process appears to be out of whack. In electricity markets, a pause is not possible. Trade must continue as electricity flows. Still, it is possible and desirable to have a circuit breaker on the scarcity pricing, triggered by the duration and frequency of scarcity events.

The ERCOT market had such a circuit breaker. Unfortunately, it was designed for a hot Texas summer with tight supply conditions. In this case, natural gas typically is priced in the $4/mmBtu range, but there may be many shortage events in the summer. Once a hypothetical peaking unit has earned three times its annual total cost ($315,000/MW), the circuit breaker reduces the shortage price from $9000/MWh to $2000/MWh, so long as the gas price is below $40/mmBtu (about ten times the typical gas price).

This summer-designed circuit breaker did not work as intended in February 2021 due to the event's long duration and the high natural gas prices. The circuit breaker set the price at the higher of $2000 or 50 times the fuel index price, which during the event climbed to $359.14, implying a shortage price of $17,957/MWh, well above the high shortage price of $9000/MWh. The PUC corrected this flaw through emergency action.

ERCOT needs to design a winter circuit breaker that recognizes the possibility of a long-duration shortage event and a high natural gas price. For example, a reasonable rule would be the higher of $2000/MWh or 15 times the fuel index price, but never more than $9000/MWh. Such a rule would guarantee that suppliers would have a strong incentive to produce, and demanders would be encouraged to conserve. The advantage of such a winter circuit breaker is that it would limit the losses of those short on energy in the real-time market and limit the number of firms that go bankrupt from a rare shortage event. Bankrupt market participants impose potential costs on the entire market. In extreme cases, bankruptcy can lead to complete market failure, as occurred in the 2000-2001 California energy crisis, when the California Power Exchange and Pacific Gas & Electric went bankrupt from high prices over months. Severin Borenstein provides many insights into the California crisis.

### *Avoid repricing, especially of forward markets*

Electricity systems are much too complex to be perfect. Someone will inevitably find errors. The best protection is careful testing with state-of-the-art development tools that limit mistakes. Catching errors early limit their adverse impact. Transparency is essential here. The thousands of eyes of the market participants and the public can catch mistakes sooner than the system operator alone.

But what should the system operator do when it confirms that an error occurred? Most often, the best response is to fix the code and report the error and its impact. Repricing should only happen in exceptional circumstances.

The NFL does not change the game score when analysis days later shows an official's bad call led to a touchdown in the first half's final second. Whether the touchdown should stand must be resolved before the second half starts. The reason is simple: the game score affected decisions throughout the second half. The same is true in electricity markets. Thousands of market participants make decisions based on the prices. An error cannot be corrected by ex-post repricing. Repricing applies different prices to the observed quantities. Yet both prices *and* quantities would change, but for the error. It is impossible to determine what would have happened if the mistake was not made. After the game ends with A beating B by 2 points, the NFL cannot later conclude, "No, B wins by 5 points once we subtract the 7 points that A received because of a bad call."

This issue is relevant in the Texas crisis in that there is a question about whether the system operator ended the shortage pricing at the right time. The point at which shortage pricing ends is complex because the quality of reserves on the system is worse than usual in this state of emergency. Poor reserve quality suggests that the system operator may choose to extend the emergency until the operator is confident that the reserves can perform. It is too early to say whether the system operator made the right call in this case. Nonetheless, the market participants relied on the prices as printed in the thousands of decisions made in the storm's final hours. There should be a strong presumption against repricing.

### *Facilitate liquid and efficient trade of forward energy*

Many have argued that the Texas market is especially vulnerable to shortage events because Texas does not have extra reserve capacity. This is false. Texas has a reserve margin, extra capacity beyond its peak needs, of about 10 percent. The Texas reserve margin is lower than most systems but is consistent with the reliability standard of the federal regulator, the North American Electric Reliability Corporation. In addition, Texas has 4 GWs, or 5 percent of peak load, of emergency demand response that serves as a further strategic reserve in emergency conditions.

ERCOT does not have a capacity market like the East Coast markets. A capacity market effectively enforces a target reserve margin. By contrast, ERCOT uses scarcity pricing to incentivize electricity-producing companies to invest in the ERCOT market. The Public Utility Commission sets scarcity pricing. Periodically, ERCOT engages independent experts to evaluate whether scarcity pricing provides sufficient incentives to invest in the ERCOT market. There have been no years where ERCOT has had insufficient capacity to date. The closing of several coal plants caused the reserve margin to be unusually low in 2019, at about 8 percent. Still, there was no problem serving the summer peak load. Because of the strong performance incentives, the generating companies took steps to make sure their units were ready for the summer of 2019. Forced outages were exceptionally low during the summer peak because of these efforts.

A lack of a capacity market was not the problem. Texas had adequate resources to satisfy demand, as confirmed in a detailed study before the winter crisis. The problem wasn't capacity; it was that nearly one-half of the resources were unable to produce energy because of frozen gas lines and the overall lack of winterization necessary to cope with the 2021 storm. The problem was a lack of resilience to freezing.

Forward markets are essential for market participants to manage risk. For example, the demand-side can purchase expected energy needs ahead of time to avoid volatile prices that emerge in real-time. Similarly, the supply side can sell energy forward to gain a steady income instead of depending on rare and unpredictable price spikes. The system operator can do more to support forward energy markets and improve the transparency of forward positions. Greater transparency reduces the potential for moral hazard—a bad actor imposing costs on others by hiding undesirable behavior.

System operators have stayed mainly out of facilitating forward markets with a few exceptions: 1) the day-ahead market for scheduling, 2) the market for congestion revenue rights, and 3) in markets with a capacity market that includes pay-for-performance, annual call options for energy during shortages.

The absence of a capacity market gives market participants flexibility in customizing forward contracts to minimize risk. However, the forward markets may have limited liquidity and competition. The system operator should support forward trading in a voluntary market to address this concern.

The alternative, a capacity market, has proven to be vulnerable to inefficiencies in the stakeholder process. Even the best capacity markets are hampered by a one-size-fits-all approach, which is increasingly difficult to justify considering the current rapid innovation in technologies. The efficient voluntary trade of forward energy is more straightforward and flexible than a capacity market.

The restructured electricity markets in the United States are among the most transparent markets anywhere. The market rules are common knowledge and unambiguously map bids and offers into market outcomes. Participant-specific bids and offers are made public after a short delay. An independent market monitor studies the data and quickly identifies issues that may adversely impact the market's competitiveness or efficiency. Transparency in financial markets is poor by comparison.

Still, regulators can improve transparency. One area is the natural gas market. Another is improved clarity over market participants' financial positions in forward-energy products. The justification for greater transparency is to provide visibility into long or short positions that may increase the possibility of defaults by counterparties. These defaults impose system-wide costs on market participants. Unbalanced positions also increase the incentive to exercise market power.

### *Add a forward-energy market for simple, transparent, and efficient trade up to 48 months ahead*

The forward-energy market is voluntary, as are the day-ahead market and the market for congestion revenue rights. It is conducted and settled by the system operator. Facilitating a voluntary forward market enhances competition, reduces overall market risk, and improves transparency, much like the highly successful day-ahead market for energy and reserves. The approach is far simpler than adopting a capacity market, especially when paired with recent financial trade innovations.

Here is a suggested proposal that would be simple to implement. Technically, a system operator could introduce it in months, not years. Since it is voluntary, there can be little objection to its introduction. Like the other forward markets operated by the system operator, the day-ahead market and the congestion revenue rights market, participants take advantage of the forward trading opportunity only if they want to. If market participants find trade is not beneficial, they do not need to use it. Unlike the other forward markets, which are necessarily complex and tightly connected to the grid's intricate details, the forward-energy market described here is simple, and the development cost is trivial compared with the other forward markets.

There is a single foundational product, monthly forward energy. It is a financial instrument to provide energy for a calendar month (or remaining month) at the system hub at a specified weekday or weekend hour. (Locational scarcity is addressed primarily in the market for congestion revenue rights, which prices the congestion between any two nodes in the network up to three years forward.) The product is a hedging instrument for managing day-ahead price risks. (Real-time price risks are managed in the day-ahead market.) Forward energy is a derivative of day-ahead energy. Deviations from obligations are settled efficiently at day-ahead prices.

Since the product specifies the type of day (weekday or weekend/holiday), hour of the day (1,…,24), and months ahead (0,…,47), there are 2 × 24 × 48 = 2304 products. The products enable any market participant to specify any demand or supply that persists for a specified month controlling for hour and day type. Demand or supply can be different every month over the four years. Such a simple product structure lets participants approximate any load shape and level, subject to the weekday/weekend constraint. The form is more powerful than in existing futures markets (CME and ICE) that only allow two products, peak and off-peak. Participants express orders as demands for simplicity and without loss of generality; offers to sell are simply negative demands.

Participants simultaneously trade products using the flow trading methodology of Budish-Cramton-Kyle-Lee-Malec. Traders submit persistent piecewise linear flow demand curves to trade in MWh per hour by product. The system conducts frequent batch auctions at regular intervals, such as once per hour. Traders may submit orders to trade portfolios of products as if they were one product. A portfolio is any linear combination of products.

As an example, a service provider may desire a particular portfolio of forward energy based on its anticipated demands by year, month, hour, and type of day. As this target portfolio changes with customers' entry and exit, the service provider can adjust to the new target with a single order. The service provider can manage the trading costs associated with price impact by expressing the rate at which it shifts from the current portfolio to the new target.

Market clearing quantities and prices are the solution to a quadratic program with linear constraints constructed by attributing preferences to orders and maximizing imputed gains from trade, just as in the day-ahead and real-time markets. Market clearing prices exist and define traded quantities uniquely. Calculating prices is computationally feasible. The prices are unique, with a simple tie-breaking rule. Thus, the market unambiguously translates orders into prices and quantities. The settlement is easy, and the system operator readily manages any required collateral calls.

This market design corrects flaws in continuous trading markets. The method reduces bid-ask spreads to zero, and it allows all executable orders to trade at the same prices at the same time. The design promotes economic efficiency by eliminating the arms race for speed and reducing messaging costs. It fosters trust and confidence by improving transparency and simplifying participation. Papers describing the approach in detail will be available in the third quarter of 2021.

Like all the ERCOT markets, the Independent Market Monitor would watch and identify problems quickly. One potential issue is the exercise of market power by a dominant participant. As in the other markets, the rules can address this market failure. One approach is an activity rule, requiring large generation owners to maintain a position in the peak months (January, February, July, and August) that corresponds to their physical capability to produce energy during shortages. The activity rule would tighten as the delivery month nears. For example, for $m \leq 48$ months ahead, a requirement of at least $100 - 2m$ percent of its estimated supply at the system peak, where supply is the aggregate capacity value—the ability to produce energy during shortage—of the supplier's resources. This is a minimum. The supplier can always sell more.

A market power test would determine whether the activity rule is imposed. For example, PJM uses a three-pivotal supplier test. In this case, a supplier's aggregate capacity value is its supply measure. For a specified supplier, we ask, "Is peak demand greater than total supply after we subtract the supply from the two-largest suppliers and the specified supplier?" If the answer is "yes," then the specified supplier is three-pivotal, and the supplier must satisfy the activity requirement. That rule or some variation would work well. Suppliers that trigger the market test may reasonably argue that such a rule should not force the supplier to sell at any price. Instead, the activity rule would also set a reserve price. The activity rule requires enough quantity to be offered at or below the supply reserve price. Thus, either the required quantity is met, or there is insufficient demand at the supply reserve price.

There are many variations to this proposal based on the setting.

In Texas, the investment environment is sufficiently strong that the simplest voluntary structure is apt to work well. The market would provide a highly transparent, simple, and efficient means for participants to adjust energy positions by month up to 48-months ahead and accommodate any month-specific production or load shape. Trading is nearly frictionless: there are no trading fees and zero bid-ask spread. Participants directly manage price impact. A more patient trader that adjusts its position more slowly reduces its adverse price impact and reduces its trading costs.

In markets where investment is more of a problem, a better design may be a mandatory market, similar to a capacity market. In this case, there would be target positions that move toward the service provider's estimated load as it approaches delivery. For example, for $m \leq 48$ months ahead, a purchase requirement of at least $100 - 2m$ percent of the service provider's estimated demand at the system peak. Again this is a minimum. The service provider can always do more.

Even in a voluntary market, there is a good case that the market power rule should be symmetric for demand and supply. Thus, based on its expected demand at the system peak, a service provider would be subject to a symmetric activity rule requiring a schedule of positions to meet or exceed by months ahead. The activity rule requires sufficient bids at or above the demand reserve price. The service provider meets the required quantity, or there is insufficient supply at the demand reserve price. The demand reserve price (e.g., $400/MWh) is much higher than the supply reserve price (e.g., $40/MWh).

Since the activity rule is applied in the four months when demand is greatest and when reliability is the most difficult, it is reasonable for the price to be above average (a supply reserve price of $40) but not wildly so (a demand reserve price of $400).

Such a forward-energy market needs to be conducted by the system operator rather than a financial exchange to address potential market failures unique to electricity. The market needs an effective information policy and market power mitigation, neither of which private exchanges support.

A forward-energy market with a symmetric activity rule to address market power has much promise. Its motivation is to improve transparency, efficiency, and price discovery. All three factors promote reliability.

[*Gentle reader: Please jump to Federal action, page 23, if you want to skip some technical details.*]

### *Consider a 24-hour rolling settlement that is more flexible and efficient than the day-ahead market*

Building on the idea of the rolling 48-month forward-energy market, a similar approach can replace the day-ahead market. This approach has yet to be implemented. I raise it as an idea to consider in future years.

The day-ahead market's motivation is to schedule resources optimally throughout the next day. The day-ahead approach is especially useful for thermal units that take four to eight hours to start. These units have complicated and costly start-up and cool-down procedures, such as coal and combined-cycle gas units—the bread and butter of the system ten years ago. The day-ahead market lets many of these units bid their characteristics and then be optimally scheduled to bring as much value from these resources as possible. But even for coal and combined-cycle units, the day-ahead commitment is often ineffective because of longer start-up procedures that require the companies to self-schedule such units. The owners simply tell the system operator when the units will run without any optimization from the system.

The electricity grid of tomorrow will have a far different composition than the traditional mix of nuclear and coal for baseload and combined-cycle and combustion-turbine gas units for peak load. There will be a much richer variety of generation types and configurations in the grid of tomorrow. For example, suppliers can configure batteries for different durations, from one to eight hours or more. Operators of modern combined-cycle units can reconfigure units on short notice. Tomorrow's market should embrace this flexibility.

The optimal configuration of resources depends on how real-time prices vary throughout the day. Texas, for example, tends to have shorter and more extreme price spikes, whereas California has prices that vary more predictably with the time of day. This difference implies that short-duration batteries are more profitable in Texas; whereas, California has more long-duration batteries to smooth net-load as the sun goes down. Existing day-ahead markets are not well-suited to the full range of battery configurations. The same goes for other new technologies. The day-ahead forward scheduling worked well for yesterday's grid but will work less well for tomorrow's grid.

The biggest problem with the day-ahead model is that it assumes the world ends at midnight. This is false, but the methods for addressing this discontinuity at midnight are imperfect and complex.

A more straightforward and more robust approach is a 24-hour rolling settlement. Under this approach, market participants express their physical and economic characteristics for the next 24 hours. These preferences persist until adjusted. The resources are then optimized to maximize social welfare, adjusting the resources' schedule throughout the next 24 hours. The system operator runs the same optimization each hour. Rather than two settlements (day-ahead and real-time), there are 24 settlements. An hourly settlement may sound complicated, but it is not. Today, the system operator reruns the day-ahead optimization throughout the day as circumstances change, but the reruns are not financially binding. Making the hourly reruns financially binding improves incentives throughout the day. And this extra step of settlement is computationally trivial.

Rolling settlement's main advantage is that it avoids the end-of-day issues that arise with the two-settlement system. For example, the optimal schedule for a battery resource is easy to determine from future prices. With a rolling settlement, prices 24 hours ahead are always known and available, enabling the batteries and other resources to be scheduled optimally. With a two-settlement system, batteries, toward the end of the day, run out of future prices to guide their behavior and optimize their schedules. The same is true for other resources that may operate across days.

One might wonder how this approach works in a voluntary market—all the forward markets in Texas are voluntary. The answer is it works fine. All resources must state their plans consistent with anticipated outcomes. Participants are required to revise plans as circumstances change throughout the day. Thus, the system operator includes plans in the optimization to consider all supply and demand. Traders can also use virtual orders to arbitrage forward and real-time prices. The day-ahead market works in the same way. A key advantage is that there would be less need for self-scheduled resources; thus, more units would offer their characteristics and be optimized by the system.

Improved incentives and no-end-of-day issues are why the rolling approach would be more straightforward and robust.

### *Improve the real-time market with a 30-minute rolling look ahead*

The efficiency of the real-time market can be improved. The approach taken in the US restructured markets is to represent the real-time market as a linear program to find the dispatch and pricing that maximizes as-bid social welfare in the current 5-minute interval (real-time) that satisfies all physical constraints. The inefficiency of this approach is that it is static. Efficiency is improved if the system looks ahead. Some offline units can start quickly; some loads can reduce demand with short notice. New constraints will appear, and others will be relaxed. Optimizing this dynamic system yields more efficient outcomes.

Today's computers and algorithms are such that it is straightforward to add this 30-minute look ahead. From 2015-2017, ERCOT studied such an approach (multi-interval-real-time market) and found it feasible; however, the benefits calculated from 2015-2016 were too small to justify the cost of implementation. Given advances in algorithms and computers, these implementation costs are now less. Further, the resource mix change suggests that the look-ahead benefits of competition and efficiency are now more significant. ERCOT and stakeholders should reconsider the approach.

The exact length of the look-ahead is not too important. The ideal likely is somewhere in the range of 30 to 60 minutes, depending on the system's mix of resources. Too short a look ahead is limiting the dynamic benefits of looking ahead; too long a look ahead is optimizing the wrong set of resources. Importantly, unlike today's five-minute dispatch, a linear program, the 30-minute look ahead would consider resources that can come online within 30 minutes. ERCOT's analysis from 2015-2017 confirmed that the challenges of including binary variables, like the decision to start flexible resources, are readily solved.

The rolling look ahead does not need to impact how the system settles the real-time market. The most straightforward approach is to use the prices from the first five-minute interval for the real-time settlement. A more complex variation is to apply the rolling-settlement process so that the five forward-looking five-minute intervals are financially binding forward transactions in a rolling settlement. The approach is readily modeled to determine the benefits of the added complexity. Logically, rolling settlement is preferred. Financially binding forward prices improve incentives for performance in real-time.

## Federal action to help Texas and other states improve the resilience of critical infrastructures

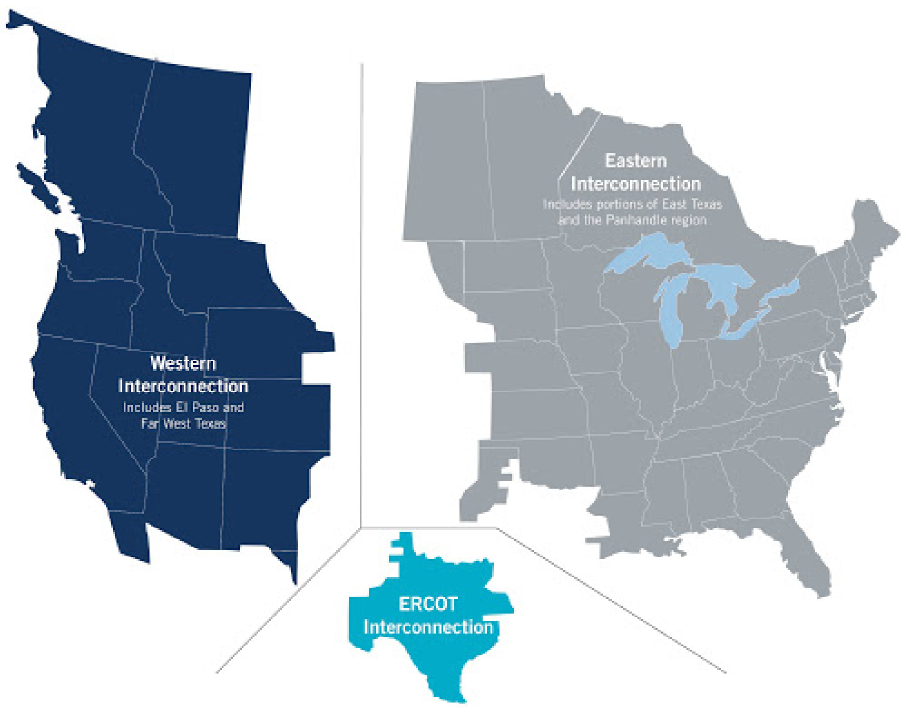
### *Use standards and grants to foster energy efficiency*

The federal government has a keen interest and responsibility in supporting the resilience of critical infrastructures. The reason is that these systems often extend across state lines. Even when they do not, linkages with other states remain. Texas's electricity shortage was caused partly by a failure of gas supply. Texas supply fell by 45 percent during the storm; national supply fell by 21 percent. The winter storm caused the price of natural gas to soar nationwide. Liquid natural gas prices soared worldwide. Even absent linkages, the federal government plays a vital role in insuring states against high-impact, low-probability events. With this insurance comes some oversight to ensure that states correctly manage risks. The federal government should bring both money and oversight to mitigate states' moral hazard.

*Strengthen the ties between the major interconnections in the United States*

Texas is unusual in being almost an electricity island with only minor connections to the rest of the United States and Mexico. Grid independence was a conscious and popular choice of Texan policymakers to remain free of regulation by the Federal Energy Regulatory Commission. If Texas had more significant ties to the Eastern and Western Interconnections, the magnitude of the February shortage would have been less. However, an economic level of interconnection would not have prevented the crisis.

*The three main interconnections in North America (Source: [ERCOT](ERCOT))*




A potential long-term improvement for the Texas market involves strengthening the linkage with the Eastern and Western Interconnections. Stronger ties would have many benefits for Texans. Large-capacity DC ties could draw gigawatts of power from neighbors to the West, North, and East, improving reliability. In the event of a complete blackout, the DC ties would facilitate a faster and more robust black start: the system operator would draw on neighboring grids' stability in the intricate process of restoring the Texas grid from a blackout. A final benefit is that Texas would export large quantities of renewable generation from its abundant solar and wind resources. In this way, Texas could continue to lead the energy future rather than be stuck in the fossil-fuel past.

Stronger interconnections with other electric systems will come at a cost—more federal regulation. Texas's avoidance of FERC regulation has allowed the Texas market to be more innovative than other markets. I believe FERC commissioners have understood the advantage of letting the Texas market develop without FERC regulation. If so, FERC's role in ERCOT might not substantially change if there were stronger ties. The political cost of FERC control would be large relative to any benefits. Thus, FERC might decide to continue a largely hands-off approach following stronger interconnection.

The worst outcome for Texas would be the politicization of the ERCOT market. An effective electricity market cannot function well when directed by partisan politics. Regulatory oversight should be independent of partisan politics. Should partisan politics impose too much on ERCOT, then one remedy is

FERC regulation. Ideally, both FERC and the PUC will represent the broad interests of electricity customers, not the powerful special interests of incumbent energy companies.

Researchers should conduct detailed modeling of the tradeoffs of stronger DC ties. Realistically, however, any implementation will take decades.

## Conclusion

The 2021 Texas electricity crisis is a wake-up call of global importance. Critical infrastructures are vulnerable as the impact of climate change grows. Infrastructures must be reinforced so that they are more reliable and resilient. Rapid innovation in how electricity is produced and consumed creates challenges and opportunities for resilience. Market designers need to find effective ways of inducing public and business behavior to improve reliability.

With additional resilience comes additional expense. For example, improved winterization of homes with caulking and insulation is expensive, but it brings considerable benefits. Such homes' improved energy efficiency reduces demand during the winter and summer peaks, lessening the need for more power plants. It also reduces the risk of frozen pipes and the ensuing damage to homes. Legislatures and regulators need to establish the broad principles and policies that guide these processes on the desired path.

The Texas electricity system is among the best, yet in February 2021, an unexpectedly severe storm caused a systemic failure of generating units. Simultaneously, the storm created an unusual surge in electricity demand. Over four days, the system operator had to shut down about 20 percent of the system because the power wasn't available. This level of outage caused enormous damage and loss of life. We cannot accept such a weakness in critical infrastructure. With care and urgency, we must strengthen infrastructures in Texas and elsewhere so that such crises do not happen again.

The conclusion from the crisis is not "markets don't work." Instead, it is "markets need to work better." Continuing the constant improvement of the market rules is the best path forward.

A resilient electricity grid requires complementary improvements in related infrastructures. Regulators must reform the natural gas market to perform well in a cold snap. Governments must encourage energy efficiency for new and existing houses based on standards and targeted grants.

Electricity is key to addressing climate change. Reliable electricity is also crucial. When it fails, we quickly learn how essential electricity is to modern life. A system blackout can tear the fabric of society.

We can build a reliable electricity market as we transition from fossil fuels. Such a system will hasten essential electrification in transportation and other sectors and bring on the energy future.

## Glossary

*Black start*—the delicate process of restoring electricity following a system-wide blackout. Supply resources are gradually added with demand, always maintaining frequency at 60 Hertz and a stable voltage. Any imbalance causes units to trip, increasing the time needed to restart the system. The black start process is facilitated with large flexible resources and ample inertia from the mass rotation at 60 Hertz. In the US, the lead examples are the large hydroelectric plants at Niagara Falls (2.7GW) and the Hoover Dam (2.1GW) and Direct Current ties to neighbors (Hydro-Québec's 2GW DC tie in New England).

*Capacity market*—a mandatory market for the system operator to buy on behalf of load enough physical resources in advance to achieve resource adequacy. Capacity is a reliability product and is measured as capacity value—the ability to provide energy during shortages. Better markets include a load-following financial obligation to ensure resources are paid based on performance. Suppliers that exceed obligations during shortages are rewarded at the value of lost load; suppliers that underperform during shortages are penalized at the value of lost load. There are no excuses for non-delivery. See Cramton and Stoft (2006) and Cramton et al. (2013) for details.

*Congestion revenue rights*—a.k.a. financial transmission rights, a financial product that pays the congestion revenue from a specific node to another in an electricity system over a specified period. Congestion revenue is measured as the difference in the two points' nodal energy prices. The nodal energy price is the system price plus the aggregate shadow price from relevant binding transmission constraints.

*Critical infrastructure*—the systems that society relies on for essential needs, including electricity, water, gas, communications, and transportation.

*Day-ahead market*—the voluntary financial market for energy and reserves in an electricity system that occurs about twelve hours before the next day. Energy and reserves are scheduled and priced in each of the twenty-four hours of the day to maximize as-bid social welfare based on bids from market participants. The optimization includes all resource and transmission constraints of the system.

*Demand response*—electricity customers reducing consumption, typically in response to price.

*Dispatchable resource*—a resource capable of increasing or decreasing energy production within a range based on the system operator's instructions.

*Distributed generation*—a.k.a. distributed energy resources, energy resources at the distribution level, typically rooftop solar or battery storage.

*Eastern Interconnection*—the major electricity grid in North America, covering everything east of the Rocky Mountains except Texas and Quebec.

*Electricity market design*—the process of developing market rules for an electricity system to satisfy specified goals such as efficiency, transparency, simplicity, and fairness (see Wilson 2002, Cramton 2017, and Wolak 2021).

*ERCOT*—Electric Reliability Council of Texas, the independent system operator tasked with balancing supply and demand every second. This is accomplished with a complex automated system that follows market rules developed in a stakeholder process with oversight from the ERCOT board, the PUCT, and the legislature.

*ERCOT market*—the electricity market operated by ERCOT, covering about 90 percent of Texas demand.

*FERC*—Federal Energy Regulatory Commission, the federal regulator of electricity systems in the United States. FERC is composed of five commissioners appointed by the President and confirmed by the Senate. No more than three can be from the same political party. Safety and reliability standards are regulated by NERC, North American Electric Reliability Corporation.

*Forward energy*—a financial product to provide energy in a specified period. The product is a hedging instrument for managing real-time price risks. Forward energy is a derivative of real-time energy. Deviations from obligations are settled efficiently at real-time prices.

*Independent market monitor*—an independent expert retained by the regulator to examine the market's operation, identify issues such as potential market failures and other inefficiencies, and make recommendations for improvement.

*Independent system operator*—the electricity grid operator tasked with balancing supply and demand every second. The operator is independent of any market participants.

*Load shedding*—the system operator involuntarily removing some demand from the system to balance supply with the remaining demand. Load shedding is an emergency response to maintain balance and stability when there is insufficient supply to satisfy demand.

*mmBtu*—metric million British thermal unit, the unit of measure for natural gas.

*Net load*—Total demand for electricity less the production of renewable resources, such as solar and wind. The system operator uses prices to optimize energy production and storage to match net load every second. On rare occasions, balancing is infeasible without load shedding.

*Peak load*—the maximum demand achieved in a specified period, typically a day, a season, or a year. The summer peak typically occurs on the hottest weekday in August. The winter peak typically occurs on the coldest weekday in January or February.

*PUCT*—Public Utility Commission of Texas is the state regulator of electricity, water, and communications. The PUCT has three commissioners appointed by the Governor.

*Railroad Commission of Texas*—the regulator of Texas's oil and gas industry, including coal, natural gas, and pipelines. Its three commissioners are elected statewide for six-year terms. One commissioner is elected every two years.

*Real-time market*—the physical market for energy and reserves in an electricity system. Energy and reserves are dispatched and priced in 5-minute intervals to maximize as-bid social welfare based on bids from market participants. The optimization includes all resource and transmission constraints of the system. Real-time prices are used to settle any deviations from forward market obligations efficiently.

*Reliability*—an electricity system's ability to satisfy 100 percent of demand. Reliability is measured in a variety of ways. All measures are related to the frequency, duration, and magnitude of shortage events in which demand exceeds supply, for example the system average interruption duration index and the system average interruption frequency index. Outages are typically short and localized. They are caused by routine events that cause demand to spike and supply to drop, such as the failure of a nuclear plant on a windless hot summer day.

*Resilience*—a system's ability to be robust to a wide range of environments and challenges. The events are rare and typically involve systemic failure of many elements. The failure of conventional generation during extreme cold is a good example. The drop in supply and the spike in demand are triggered by the same event—extreme cold. Events are often system-wide, long in duration, and have implications for other critical infrastructure.

*Resource adequacy*—an electricity system state indicating sufficient physical resources to achieve a high reliability standard. The measurement of physical resources is based on the resources' capacity value, the ability to provide energy during shortages.

*Restructured market*—a centralized and regulated market in which 1) generating companies compete in a wholesale market to satisfy demand and 2) service providers compete in a retail market to serve customers. Restructured markets were introduced in the 1990s to replace a monopoly utility operating under rate-of-return regulation.

*Scarcity pricing*—a pricing approach that applies in near-shortage and shortage conditions. Administratively set high energy and reserve prices whenever the electricity system approaches shortage. The price equals the value of lost load, which is $9000 in Texas when the system operator must violate a reserve constraint for a significant duration. The regulator sets the value of lost load following a stakeholder process. Scarcity pricing is the regulator's expression of consumers' preference for reliability (see Cramton and Stoft 2006 and Hogan 2013). Reliability is an issue so long as there is a positive probability of load shedding.

*Systemic failure*—the failure of a system often triggered by multiple causes.

*Western Interconnection*—the major electricity grid in North America, covering everything west of the Rocky Mountains except for Alaska and Hawaii.

## References


Ausubel, Lawrence M, Peter Cramton, Marek Pycia, Marzena Rostek, and Marek Weretka (2014) "Demand Reduction and Inefficiency in Multi-Unit Auctions," *Review of Economic Studies*, 81:4, 1366-1400.

Borenstein, Severin (2002) "The Trouble with Electricity Markets: Understanding California's Restructuring Disaster," *Journal of Economic Perspectives*, 16:1, 191-211.

Budish, Eric, Peter Cramton, Albert S. Kyle, Jeongmin Lee, and David Malec (2021) "Flow Trading," Working Paper, University of Cologne.

Cohen, Judah, Laurie Agel, Mathew Barlow, Chaim I Garfinkel, Ian White (2021) "Linking Artic Variability and Change with Extreme Winter Weather in the United States," *Science*, 373, 1116-1121.

Cramton, Peter (2017) "Electricity Market Design," *Oxford Review of Economic Policy*, 33:4, 589–612.

Cramton, Peter, Emmanuele Bobbio, David Malec, and Pat Sujarittanonta (2021) "Electricity Markets in Transition: A multi-decade micro-model of entry and exit in advanced wholesale markets" Working Paper, University of Cologne.

Cramton, Peter, David JC MacKay, Axel Ockenfels, and Steven Stoft (2017) *Global Carbon Pricing—The Path to Climate Cooperation*, MIT Press.

Cramton, Peter, Axel Ockenfels, and Steven Stoft (2013) "Capacity Market Fundamentals," *Economics of Energy & Environmental Policy*, 2:2, September.

Cramton, Peter and Steven Stoft (2006) "The Convergence of Market Designs for Adequate Generating Capacity," White Paper for the California Electricity Oversight Board.

Gates, Bill (2021) *How to Avoid A Climate Disaster*, Penguin Random House.

Griffith, Saul (2020) *Rewiring America*.

Gruber, Katherina, Tobias Gauster, Peter Regner, Gregor Laaha, and Johannes Schmidt (2021) "Profitability and Investment Risk of Texan Power System Winterization," *Nature Energy*, submitted.

Hogan, William W (2013) "Electricity Scarcity Pricing Through Operating Reserves," *Economics of Energy and Environmental Policy*, 2:2, 65-86.

Larson, E, C Greig, J Jenkins, E Mayfield, A Pascale, C Zhang, J Drossman, R Williams, S Pacala, R Socolow, EJ Baik, R Birdsey, R Duke, R Jones, B Haley, E Leslie, K Paustian, and A Swan (2020) "Net-Zero America: Potential Pathways, Infrastructure, and Impacts," Interim Report, Princeton University.

Magness, Bill, "Review of February 2021 Extreme Cold Weather Event – ERCOT Presentation," Urgent Board of Directors Meeting, ERCOT, February 24, 2021.

National Academies of Sciences, Engineering, and Medicine (2021) *The Future of Electric Power in the United States*, Washington, DC: The National Academies Press.

Wilson, Robert (2002) "Architecture of Power Markets," *Econometrica*, 70:4, 1299-1340.

Wolak, Frank A (2021) "Wholesale Electricity Market Design," in Glachant JM, Joskow P, Pollitt M., eds., *Handbook on the Economics of Electricity*, Northhampton: Edward Elgar Publishing.