

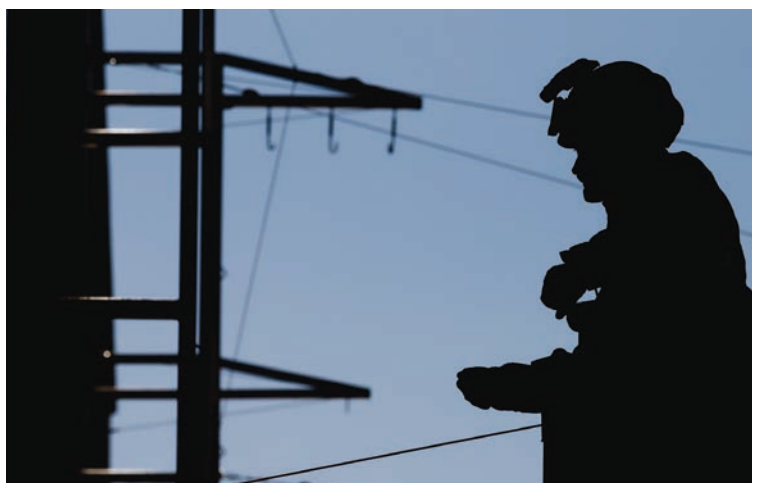


Power outage rapid response toolkit

2026 Update

By Michael Hogan and Dominic Scott

September 2026



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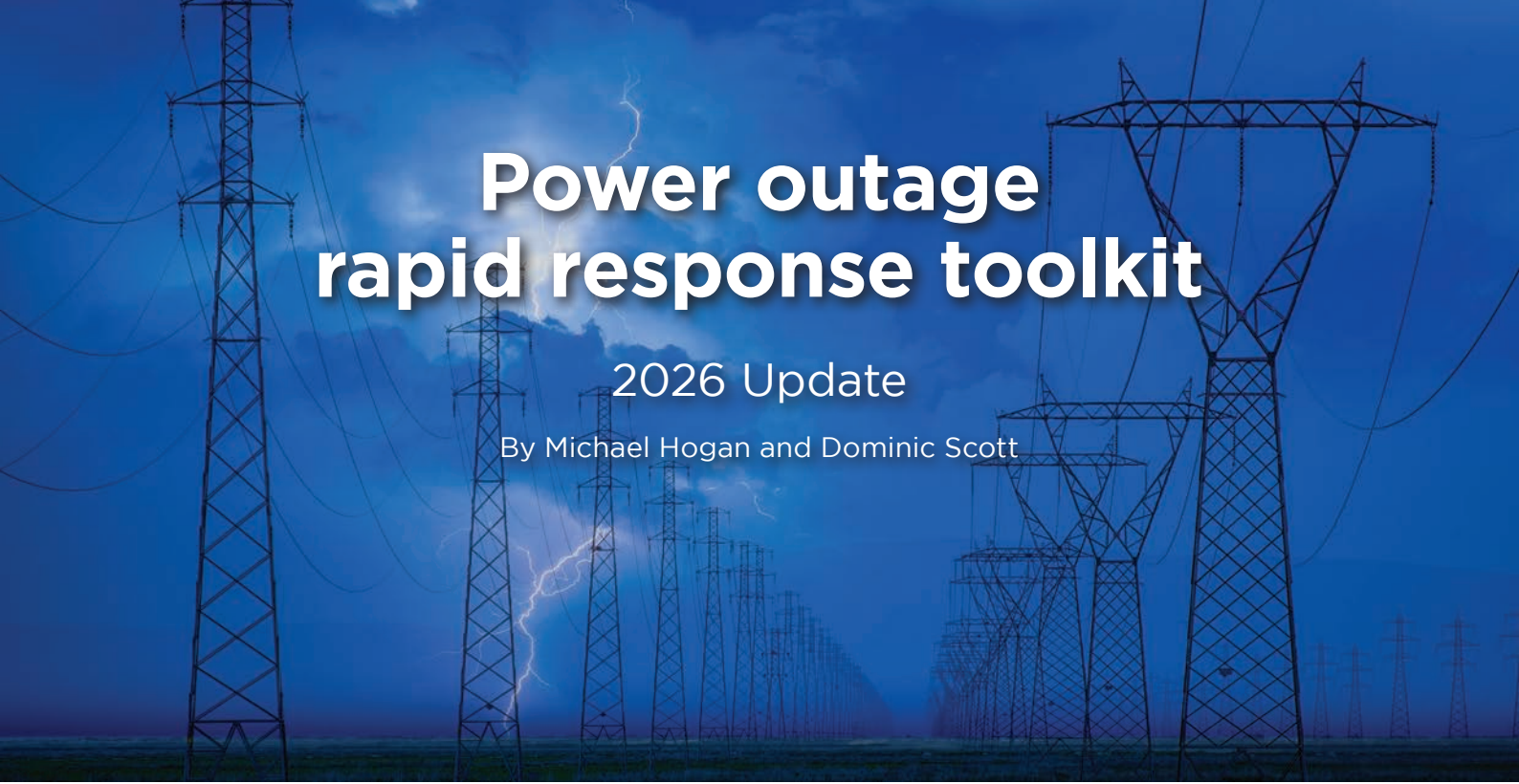
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A list of power grid outage experts is available upon request. Please contact RAP and the authors for more information.

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Introduction

Interruptions in electricity supply – ‘the lights going out’ – make for arresting headlines about ‘**blackouts**’ that capture public attention. The messy reality of what actually happened and why can get lost quickly in hyperbole and self-interested finger-pointing, leaning on cherry-picked details and seductive narratives. None of the recent events that occurred in markets with high shares of renewables have been caused by over-reliance on variable renewables in the supply portfolio. Nevertheless, the fossil energy industry has a track record of seizing any opportunity to promote the narrative that more fossil generation is needed and that the growing shift to renewables is undermining and driving up the cost of secure supply.

It is therefore important that advocates for a clean energy transition can set the record straight quickly, credibly and substantively. This package is designed to equip these stakeholders with information and tools to respond quickly to the misinformation that spreads rapidly in the wake of power grid **reliability** events.

We analysed the details of five significant outage events in grids with comparatively high shares of variable renewable generation – the Iberian

blackout of 2025, the Texas 2021 and California 2020 events in the United States, Great Britain’s 2019 outage and South Australia’s 2016 blackout – which are included as case studies. We also offer a representative list of lessons learned about good practice from the case studies.

Only two of the incidents meet the criteria for a ‘blackout’ – Iberia and South Australia. In all five cases, the fossil-fuel industry was quick to point the finger at renewable energy. With the benefit of time and independent expert analysis, we identified the root causes of the outages. Our analysis led to these key conclusions:

- Over the past decade, an era of rapid growth of renewable energy generation, **not a single major outage was caused by over-reliance on renewable energy or a shortfall of investment in dispatchable generation capacity**.¹ Each was caused by failures in transmission or fuel-supply infrastructure; a combination of both fossil

¹ International Energy Agency (IEA). (2026). *Electricity 2026: Analysis and forecast to 2030*. <https://www.iea.org/reports/electricity-2026>; IEA. (2025). *Electricity 2025: Analysis and forecast to 2027*. <https://www.iea.org/reports/electricity-2025>; IEA. (2024). *Electricity 2024: Analysis and forecast to 2026*. <https://www.iea.org/reports/electricity-2024>

and renewable generation failures; or failure to update planning, regulation and **grid codes**; as well as the lack of enforcement to reflect the changing resource mix and lessons learned elsewhere.

- **A grid with significant renewable generation can be just as reliable as any other grid.** A competent grid operator, with the authority and resources needed to enforce fit-for-purpose grid codes, can operate a high-renewables system reliably using well-understood and widely available tools.
- **Energy industry regulators can help or hinder the transition to modern grid operation.** In their oversight capacity, regulators can require these updated modes of operation and best practices.
- **Dispatchable does not mean ‘always available.’** As demonstrated by the real-world case studies we review, dispatchable fossil and nuclear plants are not always available when needed and can cause outages. This uncertainty is manageable. **System operators** have always faced the challenge of planning around the likelihood of generation being unavailable when it’s most needed. Reliability is a system attribute and is not dependent on any specific class of resources.
- **Synchronous resources are simply the most familiar way to counter sudden disturbances in frequency and voltage.** They are not the only way to do so and can be less accurate and less effective in doing so than more modern alternatives such as batteries with the right capabilities.
- **The variability of renewable energy is well understood.** Batteries are increasingly helping

to re-shape supply to meet demand.

There is also vast potential to shape demand directly to match the availability of supply — often at a fraction of the cost of batteries or construction of rarely used fossil fuel infrastructure — thereby reducing the cost of reliability for all consumers.

Reliability is a system attribute and is not dependent on any specific class of resources.

These conclusions are a useful starting point for those combatting misinformation, especially following a significant grid outage. In the critical hours during and immediately following an event, while the details are still coming to light, advocates and others on the ground can point to the precedents of past events.

This toolkit includes the following components:

- An overview of the causes of grid outages and the role of the system operator
- A checklist for unpacking the true causes of a reliability event
- Five case studies of outages, including useful reports and references
- An overview of good practice with links to relevant event cases
- Common themes and talking points to counter myths
- A primer on reliability and **resilience**
- A best-practice case study
- A glossary of useful terms and concepts (glossary terms are in **bold** in their first usage for easy identification)

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Grid outages: Causes and consequences

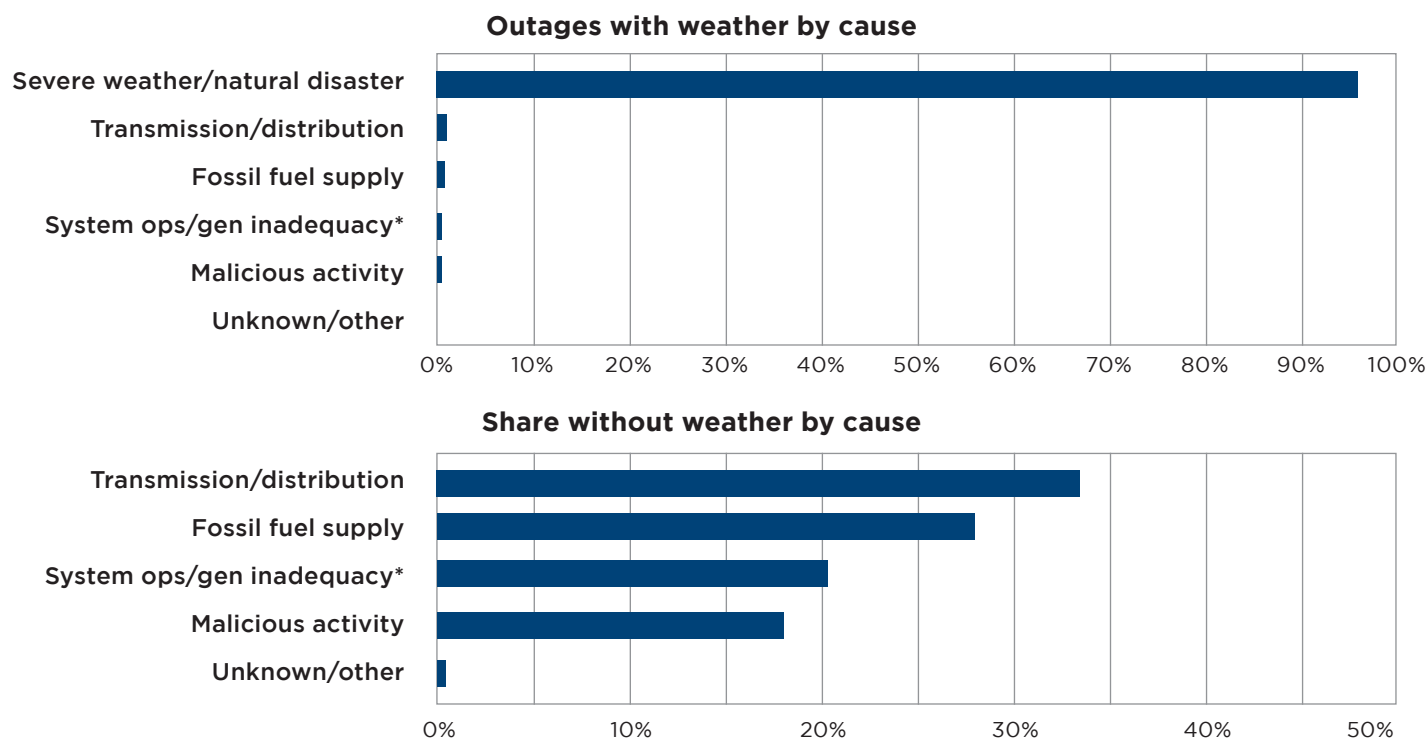
Each grid outage or reliability event (see Annex I for discussion of reliability) has its own peculiarities, but it will have as its root cause at least one of the following:

- Loss of **grid stability** due to a sudden, overwhelming loss of transmission, distribution or generation components, most often due to extreme weather or natural disaster.
- Actions taken by system operators to safeguard grid stability when faced with a threat of losing multiple critical grid components ('system operations').
- Unforeseen demand patterns: for example, from a historically rare spell of extreme temperatures that increases demand for power

or for fuels required for generation.

The overwhelming majority of service interruptions – particularly the longest and deepest interruptions – are traceable to extreme weather or natural disasters and network issues.² The U.S. survey of causes of outages by Pacific Northwest National Laboratory depicted in Figure 1³ below offers a case in point. Extended, wide-ranging outages caused by system operations or inadequate generation are extremely rare. As described in the case study of the severe winter storm in Texas in 2021, the event was an exception requiring drastic system operations to preserve grid stability. The weather dependency of variable renewables was not a major factor.

Figure 1. U.S. customer electric outages, 2014-2023



* Generation inadequacy was the reported cause in only 1.7% of the mean customer-hours included in this category.

² IEA, 2026; IEA, 2025; IEA, 2024.

³ Share of reported outages by reported cause as a percentage of mean customer-hours of service interruption (event duration times the mean number of customers affected). Source: Pacific

Northwest National Laboratory, using outage data reported to the U.S. Department of Energy, U.S. Census Bureau population data, and Oak Ridge National Laboratory geo-locational data, accessed 6 July 2026 at <https://catalog.data.gov/dataset/event-correlated-outage-dataset-in-america>.

System operator's role in preventing outages

It is the job of a system operator, the designated 'traffic cop' of the electricity highway, to ensure that the demand for and supply of energy are balanced at every moment. The grid operates on **alternating current** (AC), a current that periodically reverses direction continuously with time. Both the amount of current itself (the electrons) and the amount of force pushing the current (the voltage) alternate in this fashion. Users of the grid, both customers and generators, rely on alternating voltage and current at a stable **system frequency**, typically 50 or 60 cycles per second. They also depend on the magnitude of the **system voltage** staying within the narrowly defined ranges of the design levels. This is called grid stability, and it is the job of a system operator to maintain it.

In an ideal case, the current and voltage alternate in lockstep with each other. In practice, however, demand includes end uses like electric motors and flat-screen televisions that, by their nature, push current and voltage out of lockstep. The voltage can lead or lag the current. The extent to which current and voltage fall out of synch with each other reduces the amount of useful work they can do. The difference between the ideal case and the amount of useful power delivered is called **reactive power**. Managing reactive power is critical in maintaining stable grid voltage, and system operators rely on various tools to do so.

The resulting challenge of all these features of an AC grid is that system operators have to balance supply of and demand for energy while keeping grid frequency and grid voltage stable within a narrow band around their target levels.

Balancing energy supply and demand calls for maintaining enough available production to serve expected demand to an economic standard of reliability. To do so, system operators must account for historically demonstrated uncertainties in forecasting both the quantity

and shape of demand, and uncertainties in the ability of individual supply resources to deliver energy at any given time. They do so over time frames ranging from years in advance to an hour or less before real time, while also ensuring there is sufficient **flexibility** in reserve to deal with normally expected minor real-time departures from expected supply and expected demand.

Maintaining grid stability, by contrast, calls for containing disturbances in frequency and voltage in the event of major, unexpected disruptions in supply and demand. This can be the sudden loss of a very large generator or transmission line, or the simultaneous loss of multiple grid components, which causes frequency to slow down. Or it can be the sudden loss of a very large load such as a data centre, which causes frequency to speed up. Either can destabilise voltage, including by disrupting the ability to manage reactive power.

In both cases – balancing energy and maintaining system stability – system operators rely on a set of tools called balancing or ancillary services to avoid service interruptions. Historically, the first line of defence to blunt rapid changes in frequency has been physical **inertia** created by very large rotating generators; the first line of defence to blunt rapid changes in voltage has been the system strength provided by strong **short-circuit ratios** inherent in large rotating generators. As the supply of large rotating generators (synchronous generation) is gradually displaced by generation connected to the grid via solid-state electronic devices called inverters (**asynchronous** or **inverter-based resources**), the supply of rotational inertia and high short-circuit ratios from synchronous generation must be replaced by other rapid-response alternatives.⁴ Grids with high shares of variable renewables are capable of providing these alternatives.

⁴ Denholm, P., Mai, T., Kenyon, R., Kroposki, B., & O'Malley, M. (2020, May). *Inertia and the Power Grid: A Guide Without the Spin*. National Renewable Energy Laboratory. NREL/TP-6120-73856. <https://docs.nrel.gov/docs/fy20osti/73856.pdf>

In the case of energy balancing, it is not unusual for imbalances in schedules of demand and supply to become apparent as the moment of delivery approaches. The traditional remedy for addressing this problem is to plan to keep more supply-side resources in reserve. However, it is just as feasible – and often more economic – to tap into flexibility on the demand side to move demand to a time when supply is expected to be more plentiful.⁵

In either case, in rare instances, system operators can misjudge supply and demand to the extent that their supply of reserves or availability of flexible demand will be exhausted. When that occurs, they can temporarily lower the system voltage (called a ‘brownout’) or direct utilities and large users to selectively shed load on a rotating basis, keeping the grid operational until such time as demand moderates or additional supply becomes available.

In the case of grid instability, the time available to correct imbalances can be very short due to very large, sudden and unexpected disruptions to supply or demand. Options for very fast response remain critical tools for blunting the initial impacts. To begin restoring frequency, system operators can activate reserves that can respond in seconds to minutes. If voltage has been disrupted, they can respond with different options for injecting or absorbing additional reactive power. If properly regulated and deployed, variable renewables and batteries are fully capable of contributing to all these critical grid stability services.

If these measures fail to resolve the destabilisation of frequency and voltage, automatic shedding of certain loads will occur in an attempt to contain the situation until other, slower tools can be deployed. However, if failures multiply due either to factors beyond system operators’ control, such as unexpectedly extreme weather, or to a failure to position enough sufficiently fast tools for containing disturbances, generators and loads can begin to shut down to protect themselves, causing a downward spiral that, in the worst case, can lead to a full blackout.

Consequences of different types of outages

At an individual customer level, the loss of electricity is problematic regardless of what caused it or how widespread it might be – but from a societal perspective, the nature of the event can matter a great deal. Table 1 provides an illustrative survey of the range of consequences different reliability events can have.

Local, distribution-level events are the cause of the great majority of interruption hours for customers. The growth of distributed renewable generation presents new challenges for system operators overseeing the distribution networks, but with prudent regulation there is no reason they should lead to more frequent interruptions.

Although these events tend to attract little media attention and are therefore not the target of this exercise, they do establish the individual consumer’s baseline experience of reliability against which other, less common types of events must be considered. The focus, however, of this toolkit is the events that attract broad, high-volume attention and misinformation campaigns: brownouts, **rotating interruptions** and blackouts, resulting from problems in the bulk or wholesale power grid.

Brownouts and rotating interruptions are an intentional (if very sparingly used) tool in a prudent system operator’s planning toolbox for maintaining system stability. This reflects the fact that it is technically unrealistic and economically undesirable to plan to never have a shortfall of supply. This is due to the exorbitant additional cost of attempting to increase system supply reliability beyond, say, 99.97%. If brownouts and rotating interruptions remain rare and

5 Hildermeier, J., Kolokathis, C., Rosenow, J., Hogan, M., Wiese, C., & Jahn, A. (2019, April). *Start with smart: Promising practices for integrating electric vehicles into the grid*. Regulatory Assistance Project. <https://www.raponline.org/knowledge-center/start-with-smart-promising-practices-integrating-electric-vehicles-grid/>

Table 1. Typical consequences of reliability events (traffic light, with red most severe impact)

	Local distribution failure	Rolling interruption (well managed)	Rolling interruption (poorly managed)	Blackout
Inconvenience	●	●	●	●
Loss of social welfare	●	●	●	●
Threat to public health	●	●	●	●
Threat to public safety	●	●	●	●
Loss of essential services	●	●	●	●
Price spikes	●	●	●	●

Source: RAP graphic

well-managed, they can have minimal social costs comparable to those associated with local distribution failures. If they're poorly managed, however, the consequences are magnified and social costs can be high (e.g., Texas 2021).

The consequences of true blackouts, meaning total grid collapse, are dire. The cause is invariably an extraordinary event such as a hurricane or a rapid sequence of otherwise ordinary events that overwhelm the system operator's ability to contain the instability. The latter was the case in the cascading transmission and generator failures that caused the 2025 Iberian blackout. With competent operation, planning and regulation employing best practice, however, there is no reason to expect that an increase in variable renewables should increase the likelihood of such events.

The bottom line is that large-scale events like those described in the case studies that follow are almost always caused by unexpected loss of multiple major grid components. These are most often associated with extreme weather events or natural disasters, with a recent increase in incidents traced to problems with upstream natural gas supply and infrastructure. There is no reason for the growth in renewables to change this, not least given the efforts of system

operators and regulators to address challenges associated with the energy transition. Their efforts include adopting and enforcing standards and regulations that harness the technical capabilities of inverter-based resources like wind and solar. These capabilities allow them to contribute to or replace all of the traditional tools used by system operators to safeguard grid stability. It also includes efforts by regulators to unlock system flexibility, such as with smart tariffs, which empowers consumers to contribute to maintaining reliability at low cost, for instance by charging their electric vehicle in a manner that supports grid security.⁶

6 Hildermeier et al., 2019.

The checklist

The checklist supports identification of the true causes of a reliability event. It considers the event background, root driver, the plan for dealing with such eventualities, and how plans were inadequate. This checklist provides a framework that can be used to debunk the claims of parties seeking to blame renewables for reliability events.

The best sources for timely information to answer checklist questions are typically the system operator, the energy regulator,

and the organisation administering energy markets. It may however take time for them to provide detailed reporting.

Before the facts are established, advocates of the clean energy transition have the opportunity to caution that any narrative blaming renewables for events is premature and nearly always turns out to be misinformation. They can also prevent others with business or political interests from seizing the narrative.

The checklist:

a. Demand and supply – what was the background?

- ☐ Was demand high, normal, or low?

b. What appears to be the root cause(s) based on best available information?

- ☐ Grid failure, generation failure, or unforeseen demand patterns?

c. What was the relative severity of the event?

- ☐ How many consumers were affected, for how long, with what specific consequences?

d. What was the system operator's resource plan for meeting demand under the relevant circumstances (assuming there was one)?

- ☐ How much operational capacity did it expect to have in reserve?

e. What was the expected role for renewables in the relevant contingency plan?

- ☐ How many gigawatts of wind and solar and other renewables was the system operator banking on being in operation under the circumstances?

f. To what extent did the system operator plan for and deploy demand flexibility?

- ☐ Did the system operator have access to voluntary curtailment by large industrial consumers for compensation?
- ☐ Are dynamic retail tariffs and smart technology widely deployed across the system?

g. How exactly did the plan fail, i.e., what was supposed to have happened that did not (not what renewables didn't do that they weren't expected to do)?

- ☐ Compared to the system operator plan, how much fossil fuel plant failed to materialise?
- ☐ Compared to the system operator plan, how much renewable energy failed to materialise?
- ☐ Was the level or shape of demand caused by circumstances that couldn't reasonably be anticipated given historical experience? Or was there a failure to adequately plan for circumstances that should have been anticipated?

h. What false claims are being promoted by fossil industry players and their enablers?

- ☐ What are they reporting in the media?

i. Why exactly are the claims false?

- ☐ How do the claims stack against the root cause (b) and details of the plan failure (g)?

j. Are there legitimate transition-related challenges manifested in the event?

- ☐ Were codes and standards for deploying renewables and batteries inadequate — either in design or enforcement — such that they failed to ensure the provision of critical grid services?
- ☐ To what extent is the grid operator reasonably able to rely on the installed portfolio of variable renewable resources (wind, solar, energy storage) under the conditions prevailing at the time of the event?

k. What best practices could a prudent regulator have employed to avoid the event:

- ☐ Were penalties for non-compliance or incentives for good performance robust enough to deliver the desired outcomes?
- ☐ Did system operators and others subject to regulation have the necessary direction and discretion to take action ex ante and in real time to avert the event?

l. What best practices could a prudent system operator have employed to avoid the event?

- ☐ Did the system operator gather accurate information on whether protective settings were appropriate to the needs of the system?
- ☐ Did the system operator have oversight of generation on the distribution network?
- ☐ Did the system operator position a prudent supply of critical services given the information available at the time?

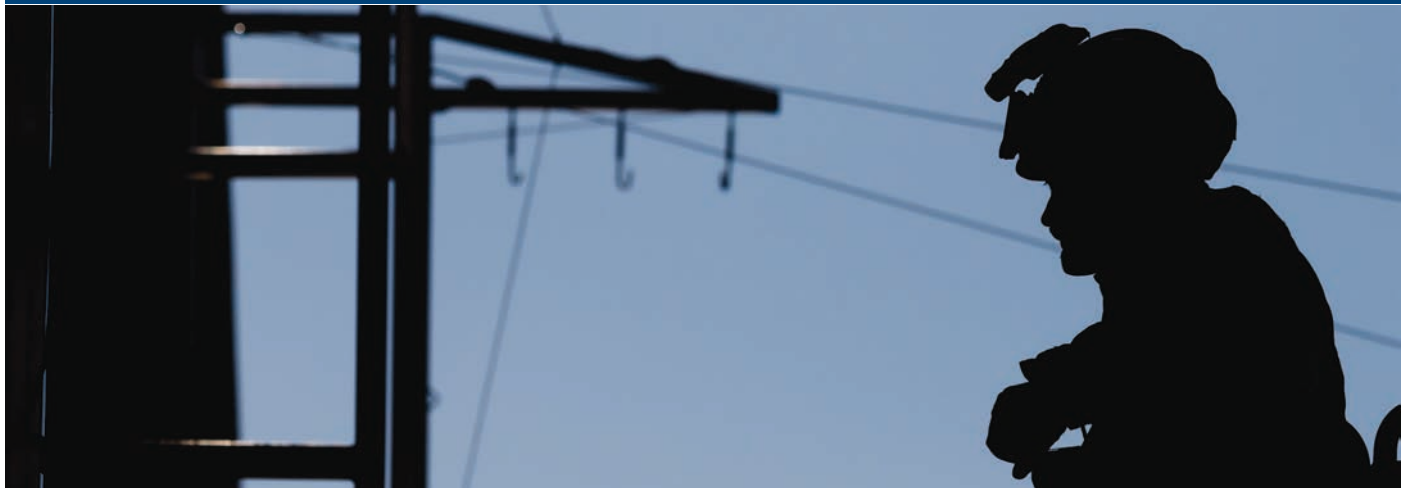
One of the case studies in this toolkit — of the February 2021 event in Texas — draws on the checklist to illustrate how it can be employed to unpack events in practice. You can find that checklist on page 34.

Five case studies

To build this toolkit, we examined five significant grid outages that drew global attention: Iberia 2025, Texas 2021, California 2020, Great Britain 2019 and South Australia 2016. We explore the primary cause of these high-profile events and debunk the myths associated with them.



Iberia 2025



Overview

On 28 April 2025, shortly after noon on a mild spring day, the electric grid spanning the Iberian Peninsula collapsed. There were no dramatic satellite photos of a black void in a sea of light because system operators were able to restore grid service in many areas by nightfall. That does not, however, diminish the seriousness of the event. Experts attributed as many as eight deaths to the blackout, and critical services were unavailable for many hours. Neighbouring balancing authorities, principally French grid operator RTE, were able to keep the event from propagating beyond the peninsula, spilling only into a small border area in France.

Like the South Australia event of 2016, this incident was a true blackout, in this case involving the de-energisation of two entire balancing control areas, Spain and Portugal. System operators were able to temper the severity of the event, completely re-energising the grid within approximately 16 hours, a notably quick restoration effort. This was aided by the fact that, like the South Australian grid, the two control areas on the Iberian Peninsula are interconnected to a much larger European grid. The same interconnectors that were de-energised to contain the spread of the event were then employed to help re-energise the peninsular system.

Demand and supply

When the incident began, demand on the Iberian grid was modest, typical of mild spring temperatures. Available resources and production on the Iberian grid comfortably exceeded demand; the interconnectors were exporting 1.4 GW from the peninsula to France at the time. Solar PV and wind constituted approximately 70% of generation in Spain. Production was markedly concentrated in southwestern Spain, with local supply rising to more than twice local demand.

Wind and solar are inverter-based resources, meaning they produce power that solid-state electronic devices called inverters must transform for injection into the alternating current (AC) grid operating at a constant frequency of 50 cycles per second.

In contrast with grids like those in Texas and California that have high shares of wind and solar, these systems had very little battery storage installed. Additionally, the peninsula was only weakly interconnected with the rest of the European grid, a potential vulnerability that had long been noted. Both of these factors were widely cited in the immediate aftermath. Although in the end they were not found to be the primary drivers of the event, they have nonetheless been identified as significant

vulnerabilities to be addressed in adopting best practice.

The plan and how it failed

Before the sequence of failures leading to the blackout, Spanish and Portuguese system operators were managing a series of frequency and voltage oscillations. Their actions helped dampen those oscillations but also left the system with less latitude to control voltage. At the start of the incident, voltage was still within normal limits, frequency was stable, and the system did not appear to be short of inertia.

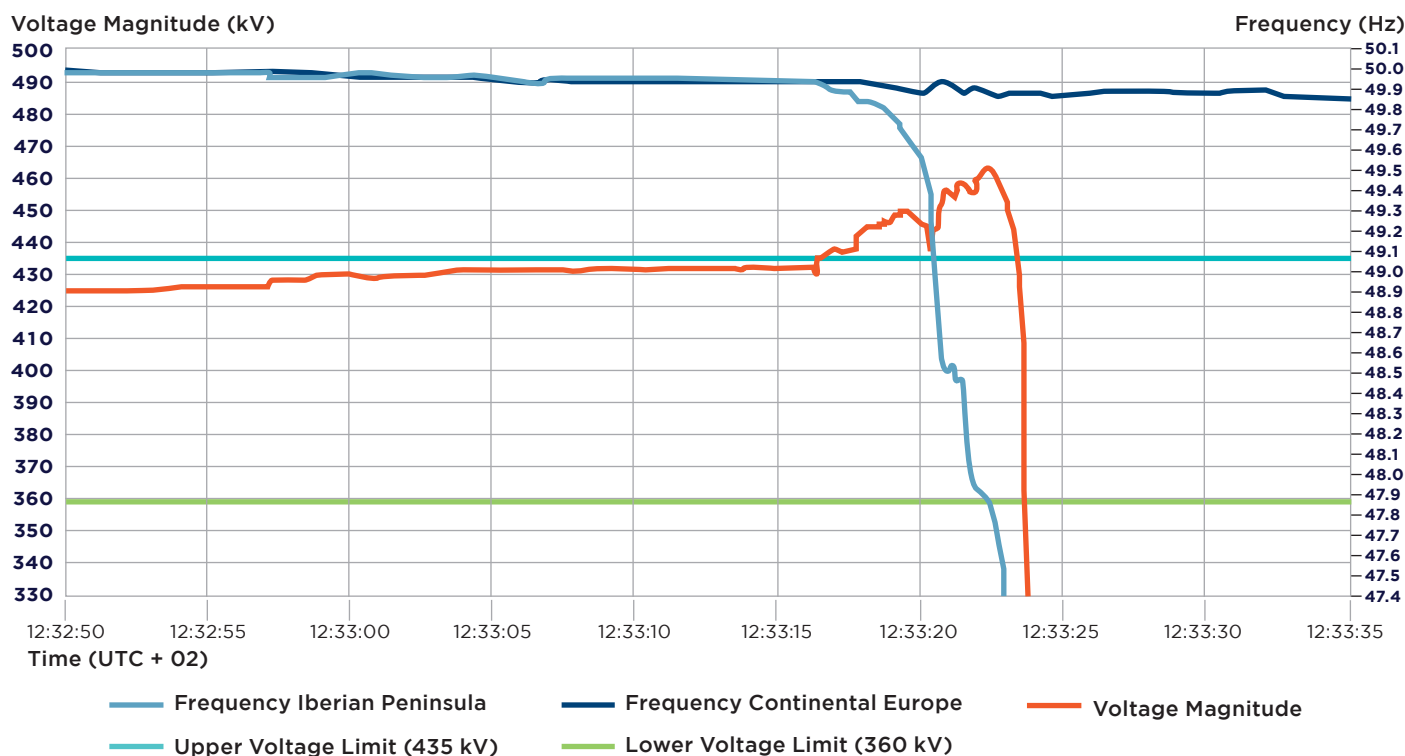
The blackout that ultimately ensued was driven by a loss of voltage control. Small generator disconnections and output reductions in southwestern Spain caused voltage to rise, as illustrated by the orange voltage line in the left half of the figure below. As additional substations

and generators tripped, many of the resources that had been helping to keep voltage under control by absorbing reactive power were lost, causing voltage to climb further.

The deterioration then accelerated. More generation tripped due to overvoltage protection settings, frequency began to fall, and automatic load shedding could not keep pace with the expanding generation loss. Operators disconnected interconnectors with Morocco and France to protect neighbouring grids and, seconds later, the Iberian system collapsed.

Forensic analyses, which took around a year to reach final conclusions, point to a complex failure in the system that keeps grid voltage stable — specifically, reactive power management. Some renewable generators appear to have disconnected prematurely, very early in the chain of events. The situation should have been

Figure 2. Evolution of frequency and voltage during the grid incident



Note: Frequency and voltage in Spain are measured at the substation of Carmona, and the frequency in the rest of Continental Europe is measured at the substation in Bassecourt, Switzerland.

Source: European Network of Transmission System Operators for Electricity (ENTSO-E). (2026). *Grid incident in Spain and Portugal on 28 April 2025*

readily manageable, however a number of other factors compromised system operators' ability to respond to the resulting disturbance. These included but were not limited to the fact that several conventional generators expected to provide stability services were unavailable or not providing the needed voltage support, and most wind and solar resources were not configured to respond dynamically to changes in voltage. The latter was particularly unfortunate, as Spain was set to commence conversion of wind and solar generators to more grid-friendly operation settings later in the year, which in itself may have been sufficient to allow system operators to avert the blackout.

Dispelling the myths

Initial speculation about the cause of the blackout targeted frequency collapse due to a sudden loss of generation, citing the high share of inverter-based resources; weak interconnection with the Central European grid; and the surprisingly small fleet of battery storage systems. Although failure to maintain a minimum level of system inertia or to provide for alternatives to manage disruptions in frequency was a factor in the 2016 South Australia event, technical analysis has determined that the level of system inertia available at the time the incident began was not a factor in the Iberian case. Increased inertia or access to more battery storage systems would not have prevented it. The cause was runaway overvoltage.

Although renewables alone were not the cause of the blackout, some renewable resources certainly contributed to it. This is hardly surprising because 70% of supply at the time was from renewables. However, their contribution to the event was not a function of the fact they were weather-dependent or inverter-based or to some extent distribution-connected. Rather, it was a function of a series of shortcomings in grid codes and code enforcement to ensure compliance. These

may have been aggravated by inadequate role clarity and coordination between distribution system operators and the transmission system operator.

Lessons

The collapse of the Iberian grid was a complex system stability failure that exposed the need for multiple corrective measures by regulators, system operators and generators. The most salient lesson in a very simple sense, however, was the failure to apply lessons learned from reliability events on other high-renewable grids.

Why the small renewable generators disconnected early in the event is not known, but it was likely due to undisclosed protection settings that caused them to trip in response to voltage that was elevated but within acceptable limits. Better oversight and enforcement of grid codes for new installations, especially on distribution grids – enabled by role clarity and coordination across distribution and transmission – may well have averted this. This was a lesson the South Australia regulator and system operator had learned nearly ten years earlier.

Had wind and solar installations been set to operate at variable rather than constant power factor, as they are in other systems with high renewables penetration, system operators probably could have brought the situation under control. Inverter-based solar and wind are fully capable of contributing to frequency and voltage regulation if regulations and rules governing interconnection require them to do so, as is the case in most systems with high penetration of inverter-based resources.

In sum, the Iberian event emphasises the crucial role regulators and system operators play in anticipating how to align protection settings and operational requirements with system needs, and ensuring strict monitoring and enforcement.

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Texas 2021



Adobe stock photo of the 2/2021 Texas winter storm

Overview

This February 2021 event was caused by a winter storm of historic depth and duration – rare but not unprecedented for Texas. More than 4.5 million customers lost power, many for three or more days. The severe conditions, in a region heavily reliant on resistance electric heat in poorly insulated buildings, led to as many as 200 deaths and billions of dollars in property damage.

Demand and supply

The cold weather drove demand to unforeseen levels. Some amount of rolling interruption over a few hours would likely have been necessary in the best-case scenario. Demand at the onset of the winter storm was above the extreme winter contingency level, more typical of Texas's demanding and very hot summer conditions. Demand peaked during the event at the highest level on record up to that time.

Supply was initially scarce but sufficient to meet the record demand. Within hours, however, nearly 50% of planned generation failed – mainly

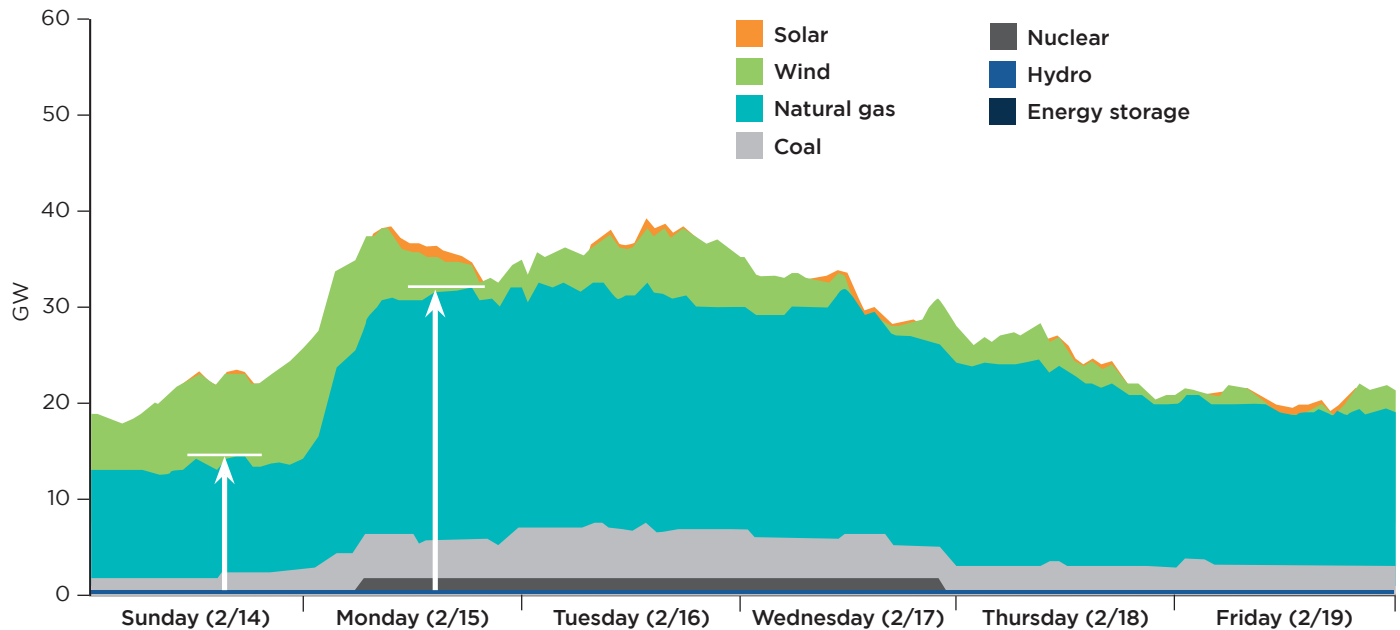
gas-fired, but also 40% of coal and one of four nuclear units. The plant failures were caused by a combination of inadequate freeze protection at the plants themselves and in the fuel supply infrastructure on which they rely. Regional gas production fell by about 50% before beginning to recover. This was all largely unforeseen.

Wind power typically supplies over 20% of Texas's *annual* electricity. Over half of the wind fleet was out of service, but the system operator plans on only about 20% of potential wind production (about 7 GW) under severe winter conditions. In the event, the fleet operated at a bit more than 10% of potential (about 4 GW, or 57% of plan in severe winter conditions) on average.⁷

This points to a very minor failure of wind, and a colossal failure of gas and coal plants. Figure 3, which plots outages of generation plant by technology, shows that the widespread service interruptions that began early in the morning of 15 February were stimulated first and foremost by a steep rise in fossil plant outages, especially in natural gas plants.⁸

⁷ ERCOT's winter resource plan includes a 'low-wind' scenario of about 2 GW. That scenario, however, is not integrated into the 'extreme' winter system demand and supply scenario.

⁸ University of Texas at Austin Energy Institute. (2021, July). *The Timeline and Events of the February 2021 Texas Electric Grid Blackouts*. <https://energy.utexas.edu/ercot-blackout-2021>

Figure 3. Net generator outages by fuel type

Note: Figure was reused and cited from an ERCOT public presentation. The outsized role played by non-renewables technologies — and especially natural gas — in the failure of generation capacity is illustrated by the difference in height of the white arrows between 14 and 15 February.

Source: University of Texas at Austin Energy Institute. (2021, July). *The timeline and events of the February 2021 Texas electric grid blackouts.*

These account for nearly the entire reduction in lost energy output that day, along with coal and nuclear failure, the vast majority of which the system operator would have been counting on. It shows that the role of lost wind output on the day was relatively modest, being not significantly higher than on the previous day. It should also be noted that the system operator did not intend to use all this output in its emergency planning in the first place.

Unlike other regions of North America, Texas's grid is effectively an island electrically isolated from neighbouring systems for historical reasons. As a result, there is limited ability to mitigate events by broadening the supply solutions. That said, as the crisis affected a broad swathe of the midcontinent, it is unclear just how much help would have been available.

The plan and how it failed

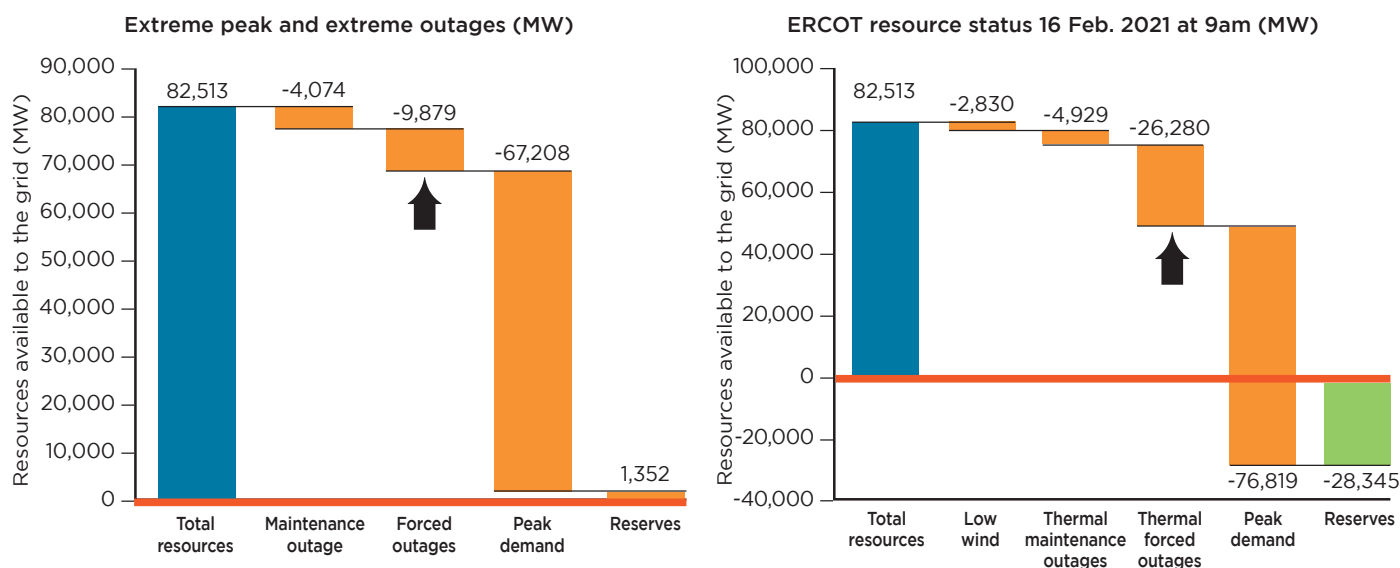
Demand of more than 77 GW exceeded the system operator's extreme winter planning scenario of 67 GW.

Available resources at the onset of the storm were roughly in line with the winter planning scenario and were stretched to the limit to meet demand. About 90% of planned generation was fossil and nuclear, three-quarters of that being natural gas. Wind generation made up the bulk of the remaining planned resources.

While the system operator would likely have had to resort to some level of rolling interruptions for a few hours as the storm continued through the week, truly dire consequences would probably have been averted had the thermal generation fleet held up as planned.

This is illustrated in Figure 4 below.⁹ It shows that the system operator, in its most extreme emergency scenario plan, planned for only about 10 GW of forced outages of generating plant based on historical experience (left-hand side). During the event, however, 26 GW of forced outages materialised (right-hand side).

9 University of Texas at Austin Energy Institute, 2021.

Figure 4. The Texas scenario (left chart) and the actual event (right chart)

Source: University of Texas at Austin Energy Institute. (2021, July). *The Timeline and Events of the February 2021 Texas Electric Grid Blackouts*.
 Note: Figures come from public data from ERCOT.

Thermal generation (that was reasonably expected to operate) failed, largely because of its reliance on natural gas infrastructure that was far more vulnerable to severe winter weather than either the system operator or the regulator anticipated. Equipment freeze-ups at the plants themselves were also a major issue. Most of the wind fleet was also frozen – that’s an issue for the future, but low output was also largely expected and accounted for in plans.

Dispelling the myths

Fossil industry actors, including the state’s natural gas regulator, were quick to point to Texas’s rapid uptake of wind over the past 20 years and the large amount of wind generation (about 18 GW of the 32 GW installed) that was offline at the time. The narrative bounced between the Texas wind fleet’s vulnerability to freezing and the effect of low wind speeds during cold winter weather on the ‘dispatchability’ of wind.

The fact that the system operator’s plan accounted for both of these factors, and that they therefore had little to do with why the disaster occurred, went conveniently unmentioned. The

claims are a familiar mix of factual snippets removed from context, woven into an intentional misrepresentation.

Lessons

The fact that the system operator’s plan to deal with these circumstances continues to be so heavily reliant on fossil fuels is a concern, as is the fact that the Texas renewables resource is so reliably unreliable under these circumstances. Both challenges call for known solutions, including on the demand side.

The following best practice could help to avoid this type of event in future:

- As extreme weather events become more common and severe due to climate change, regulators and system operators will need to update their scenario planning based on the trends evident in more recent historical information, including this event.
- There should be stronger oversight and ‘no excuses’ enforcement of operational standards for critical resources, including the upstream infrastructure on which they rely.

- Aggressive deployment of end-use efficiency measures, such as heat pumps to replace electric resistance heat and improvements in building insulation, is required to increase demand flexibility, reduce overall demand, and safeguard public health.
- There is a need for implementation of smart distribution-level technologies and smart pricing to adequately incentivise shiftable loads to be shifted away from peak hours without unduly inconveniencing end-use customers.
- The distribution system should be better sectionalised to allow more targeted control over what demand gets protected (e.g., critical infrastructure) and what is available for rotating interruption.
- The Texas grid's linkages with neighbouring systems should be increased to expand options for dampening the impacts of future such events.

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California 2020



Adobe stock photo of California wildfire

Overview

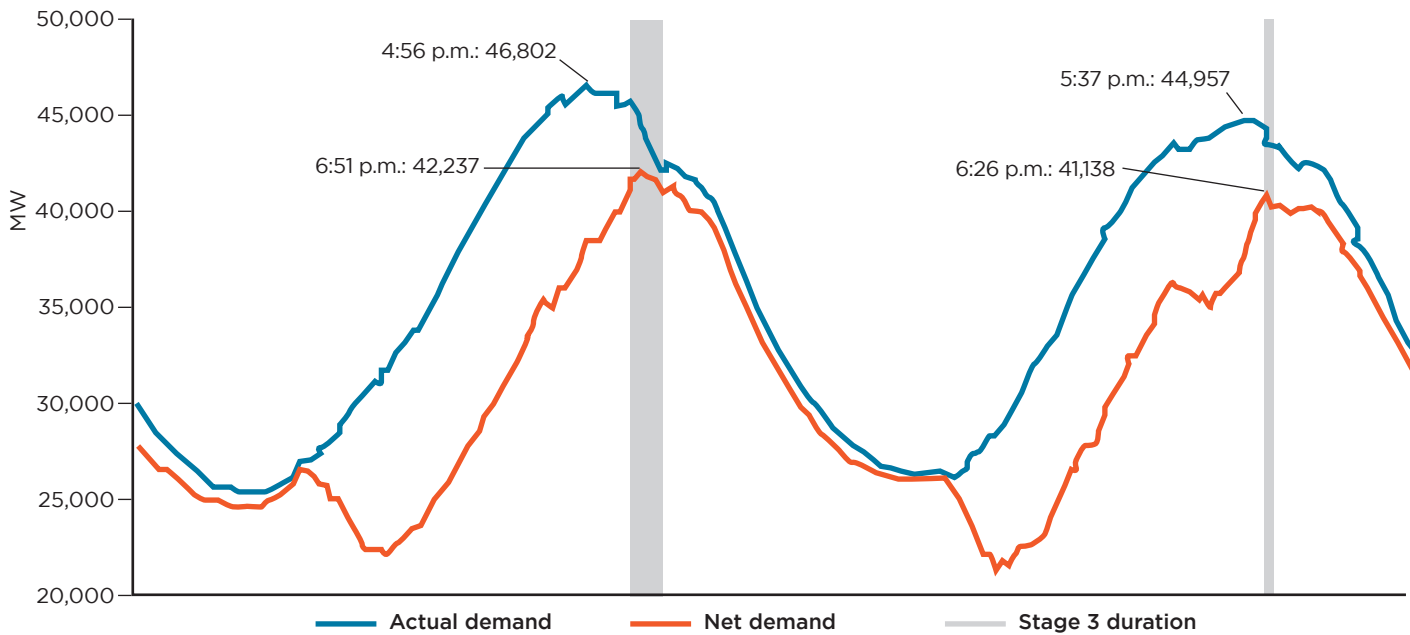
From 14-19 August 2020, western North America – extending from northern Mexico to British Columbia, and from the desert interior to the Pacific Coast – experienced a severe and extended heat event of historic dimensions. This occurred during a summer that overall had been hotter and drier than normal across the West. Much of the attention around this time was on the recurrence of what have become increasingly frequent and intense wildfires. The causes of some of the highest-profile and most catastrophic wildfires in recent years have been traced to downed high-voltage transmission infrastructure. To reduce risks to life and property and the associated financial liabilities, some of the utilities that own the region's transmission facilities have begun pre-emptively de-energising transmission facilities under certain conditions, at times blacking out large areas in the region for days or even weeks at a time. Mid- to late-August 2020 saw an especially dangerous convergence of these factors, with large wildfires burning out of control along the West Coast, extreme heat and drought conditions even in the normally cool, damp Pacific Northwest, and higher-than-normal, unusually round-the-clock air conditioning and refrigeration loads, especially in the Desert Southwest region.

It was against this backdrop that, in the early evenings of 14 and 15 August, the California Independent System Operator (CAISO) was forced to order distribution utilities in its footprint to initiate a series of controlled firm load curtailments. This measure cut service to rotating groups of customers over a one-hour period on 14 August and a 20-minute period on 15 August, in order to preserve the minimum level of contingency reserves required to ensure that a major unplanned event – such as the failure of a major transmission line or the shutdown of the system's largest power generator – would not lead to a catastrophic system failure across CAISO and beyond. The load sheds ordered by CAISO were for 500 MW on both days, or approximately 1.1% of actual firm demand in each case.¹⁰

Demand and supply

The extreme heat event that began on 14 August and carried on until 19 August amounted to a 1-in-30-year meteorological event in California, based on historical data for intensity and duration. There is little precedent for similarly extreme

¹⁰ Pacific Gas & Electric customers experienced interruptions of up to 150 minutes on 14 August and up to 90 minutes on 15 August due to logistical issues, and for the same reason actual demand shed was slightly higher on both days.

Figure 5. CAISO demand and net demand for 14 and 15 August

Source: CAISO. (2021, January). *Final Root Cause Analysis, Mid-August Heat Wave*.

Note: Licensed with permission from the California ISO. Any statements, conclusions, summaries or other commentaries expressed herein do not reflect the opinions or endorsement of the California ISO.

weather conditions simultaneously affecting regions to the north, south and east of California. Yet while actual peak demand across the entire region on both days exceeded forecasted peaks, in CAISO's control area voluntary demand response and activation of interruptible loads played a critical role in reducing actual peak demand. As a result, peak demand for energy exceeded forecasted peak by only 4.6% on 14 August and by a mere 0.5% on 15 August.¹¹ In fact, peak demand was higher later in the week as the cumulative effects of the multi-day heat event intensified, yet no firm load shed was required. (It's also worth noting peak demand was well below CAISO's then-historic peak demand of 50.1 GW,¹² which occurred in 2017 and was 7% higher than the 14 August peak of 46.8 GW.)¹³ More to the point, the order to shed firm load occurred not when demand peaked, but nearly

two hours later on 14 August and nearly one hour later on 15 August, when *net demand* peaked. Net demand is the residual load to be met by more expensive non-variable resources once the load covered by low marginal cost variable resources like wind, solar and run-of-river hydro (principally solar) is netted out. This net load profile is the result of the normal pattern of variable production – with solar production ramping down late in the day – that is well understood and is factored into CAISO's resource planning. Like peak gross demand, peak net demand was also higher later in the week, as shown in Figure 5, yet no load shed was required.¹⁴

Taken together, this illustrates that the shedding of firm load on these two days was not driven by demand that was dramatically in excess of forecast, or by a shortage of investment in

¹¹ CAISO. (2021, January). *Final Root Cause Analysis, Mid-August 2020 Extreme Heat Wave*. Figure 4.3. <http://www.caiso.com/Documents/Final-Root-Cause-Analysis-Mid-August-2020-Extreme-Heat-Wave.pdf>

¹² CAISO. (2022). *California ISO Peak Load History 1998 through 2022*. <https://www.caiso.com/documents/californiaisopeakloadhistory.pdf>

¹³ CAISO, 2021.

¹⁴ CAISO, 2021.

generation resources, or by an unanticipated problem with variable resources. As the then CAISO CEO Steve Berberich said after the event, “What caused the [firm load shed] was a lack of putting all the pieces together... You have to rethink these old ways of doing things, and I think that’s what didn’t happen.”¹⁵

The plan and how it failed

CAISO’s resource planning process is more complex than in many regions. In addition to the rapid growth in wind and solar production (with much of the solar behind the meter), the native resource portfolio includes a large amount of hydroelectric generation with limited reservoir storage capacity. The system is also heavily interdependent with neighbouring regions connected over long distances by high-voltage direct current transmission lines. Resource plans in each region are reliant on large amounts of power flowing in one direction under certain conditions (e.g., daytime vs. night-time, or summer vs. winter) and in the opposite direction under the obverse conditions. As already noted, even given the severe operating conditions that prevailed on these and the following days, the supply of resources was sufficient to meet peak demand for energy and the planned level of system reserves. The order to shed firm load occurred only later as demand was beginning to ramp down. Solar production was also ramping down and CAISO was attempting to ramp other resources up (or dispatch more demand response) to meet demand and maintain the required level of contingency reserves. While this is a daily challenge that CAISO manages regularly and managed successfully later in the week under comparable circumstances, on these two days its efforts fell short.

Dispelling the myths

Why this occurred is complicated. While the operational challenge exists in part because of the known production characteristics of wind and solar – particularly solar – there was nothing especially unusual about production from either resource on those days. During the time of the net peak at that time of year, the planned contribution of solar and wind combined would have met about 10% of what was needed, or about 4,100 MW. Solar production on 14 August – the more challenging of the two days – was near normal for that time of year, while production was lower on 15 August due to cloud cover in the north; production on both days was affected by smoke from wildfires. Solar production during the net demand peak fell short of the resource plan by about 1 GW on both days. Wind production was somewhat lower than normal and below the resource plan by 640 MW on 14 August and 230 MW on 15 August.¹⁶ These lower wind and solar production levels, while unfortunate under the circumstances, both fall within the level of variability around which CAISO would normally manage successfully.

Customary operating challenges were certainly exacerbated by the challenging weather conditions, but the overall resource situation was adequate – due, for instance, to the fact that despite a 900 MW derating of one of the major import lines from the north, imports performed well above expectations. In the end, the inability to meet net peak demand on these two days was the result of a combination of factors that compromised CAISO’s ability to fully respond to the usual evening ramps. Nearly 10% of the natural gas generation fleet, about 60% of what was expected to meet the ramp up of demand to peak, and normally a reliable source

15 Hering, G. & Stanfield, J. (2020, September 25). ‘You have to rethink these old ways’: Parting advice from CAISO’s retiring CEO. *S&P Global Market Intelligence*. [https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/you-](https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/you-have-to-rethink-these-old-ways-parting-advice-from-caiso-s-retiring-ceo-60481529)

[have-to-rethink-these-old-ways-parting-advice-from-caiso-s-retiring-ceo-60481529](https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/you-have-to-rethink-these-old-ways-parting-advice-from-caiso-s-retiring-ceo-60481529)

16 CAISO, 2021.

of flexibility for following the evening ramp, was on a forced outage. And due to a complicated set of circumstances, both CAISO and the retail suppliers had significantly under-scheduled day-ahead demand, meaning resources that normally would have been online and able to follow the evening ramp were not committed in time to do so. As the CAISO CEO said, ‘...a lack of putting all the pieces together.’¹⁷

Lessons

The causes of the event were multiple and complex, as is usually the case. While the variability of renewables figured in the chain of events, this had been well understood and planned for. Wind and solar both delivered less than had been scheduled, but the difference was within a normal range of uncertainty. There were a number of components of the plan to accommodate that variability and uncertainty in a reliable grid that, on those two days, failed.

Some of the failures were of a conventional nature, such as a higher-than-normal number of forced thermal plant outages – this was unfortunate and was perhaps exacerbated by the extreme weather, but it’s the sort of thing

for which contingency reserves are retained. Harder to justify were the decision to allow planned thermal plant outages in the middle of an unusually difficult summer peak season, and the miscommunications that led to the failure to commit available flexible generation online in advance of the evening ramp. Finally, there were the failures in adapting the planning process itself in ways that would ensure the system remains reliable as it transitions. This included a failure to incorporate what are likely to be more frequent and more extreme weather events into the planning process to account for their impacts on both demand and on supply. It also included the need to update resource planning tools to account for the fact that resource adequacy can no longer be measured (to the extent it ever could be) by the amount of capacity available during a few peak demand hours. While demand flexibility played a crucial role in limiting the scale of this incident, there is broad agreement that it has much more potential, and that the planning process needs to play a more active role in empowering consumers to take more control over how much electricity they need and when they need it.

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¹⁷ Hering & Stanfield, 2020.

Britain 2019



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Overview

The events of 9 August 2019 were triggered by a lightning strike on a transmission line. This led to loss of large wind and gas generation resources, as well as small-scale solar and small diesel engines connected to the distribution system (**embedded generation**). This loss of generation exceeded the loss the system operator was prepared for. As a result, roughly 1 million customers lost power for around 15 to 45 minutes. The event points to the importance of proper regulation to provide plant oversight, especially of embedded generation, and to ensure they are not overly sensitive to changes in system frequency.

Demand and supply

On 9 August 2019, wind provided 30% of energy, gas 30%, nuclear 20%, interconnectors 10%, and embedded generation – generation on the distribution network – contributed the remaining 10%. Demand was reported as not unusually high.

A lightning strike quickly led to the sustained loss of generation output from a wind farm,

a gas-fired power plant and multiple small, embedded generators – solar, wind and some reciprocating engines (fuelled by diesel or gas).

The plan and how it failed

It was a windy day with low demand, and as such there was low inertia on the system – requiring additional measures to manage sudden changes in system frequency. Nonetheless, the system operator had ensured adequate levels of inertia to cover the largest expected loss of energy onto the grid on the day, and was therefore delivering on its plan.

The wind plant that failed in response to the effect of the lightning strike on the network was not yet fully commissioned and was under a temporary plant protection scheme. This allowed the plant to turn off in response to changes in grid frequency to protect itself. The system operator was unaware of this arrangement. The unexpected contribution of the wind plant to the event thus stems from an absence of oversight and proper regulation, unrelated to the variable nature of this renewable resource.

Why the gas plant failed is less clear.¹⁸

Nevertheless, it appears to have contributed as much to the supply failure as did the loss of the wind plant.

The rapid-fire and apparently unrelated failure of these two plants triggered further perturbations in system frequency. Embedded generation subsequently tripped offline in response due to its own overly sensitive protection schemes. The combined generation outages exceeded the contingency scenario underlying the system operator's resource plan. This pushed the system past its limits.

Thus, the failure in planning appears to link first with the failure to address unnecessarily sensitive energy generation under-frequency protection schemes. This was compounded by a lack of system operator oversight of embedded generation, and an inadequate supply of inertia services to mitigate the impact of the combined events.

Dispelling the myths

One day after the blackout the *Daily Mail* reported “experts blame the UK's over-reliance on wind energy for the worst power cut in years.”¹⁹

It is disingenuous, to say the least, to blame the event on renewables.

While the tripping-off of a wind farm on under-frequency protection contributed to the event, that failure was not related to the fact that it was a wind farm, but rather to the combination of unfortunate timing and a failure to notify the system operator appropriately. It

is noteworthy that several other offshore wind farms, electrically closer to the initial fault, were unaffected.

If reliance on variable generation played a role, it was the reliance on embedded solar, not wind, and again the failure was unrelated to the variability of the resource. It was instead caused by a lack of information and the incomplete implementation of new rules to ensure this embedded generation supports, rather than detracts, from system reliability. In other words, it was unfortunate that the event occurred before the changes in the grid code could be fully implemented. Note that embedded generation included both diesel engines and renewables, and the variability of the latter was not identified as a driver of the event.

Lessons

The first lesson is that smart regulation is necessary to ensure that plant, including embedded generation, is not needlessly sensitive to changes in frequency. The system operator had initiated a programme of upgrading the under-frequency settings of embedded solar generation, but the project was still several years away from completion. A plant that is operating, but formally still in commissioning stage, should be notified to the system operator, and this need is not specific to the type of generation.

Second, greater oversight of embedded generation is required. Indeed, a register of embedded generation capacity above a particular threshold was approved by the regulator in 2020.²⁰

18 For instance, RWE confirmed that for “reasons presently unknown, after approximately 1 minute the first gas turbine tripped due to a high-pressure excursion in the steam bypass system.” See: National Grid. (2019, September). *Technical Report on the events of 9 August 2019*. <https://www.neso.energy/document/152346/download>

19 Bucks, J. (2019, 10 August). Revealed: Britain was hit by TWO blackout ‘scares’ in the last three months. *The Mail on Sunday*. [Article has become unavailable since original report.]

20 Ofgem. (2020, July). DCP350 – *Creation of Embedded Capacity Registers: Decision*. <https://www.ofgem.gov.uk/publications/dcp350-creation-embedded-capacity-registers>

Third, and for the longer term, the underlying philosophy of shutting down all embedded generation on loss of grid power until the grid is restored needed replacing with something more appropriate for the future. The system operator has since identified best practice for deployment of grid-forming inverter technology as an important measure to mitigate this issue.²¹

Finally, the system operator ensured adequate levels of inertia to cover the largest expected loss of energy supply onto the grid on the day, and

its final report suggests that its actions before and during the events were in accordance with industry requirements. It is appropriate, however, to revisit the arrangements — the formulation of system operator plans — for maintaining the resilience of the system during extreme events as the energy mix changes. A focus on procuring sufficient system inertia and inertia replacement options is necessary in the face of growing renewables, and the system operator has reinvigorated its focus on this in the interim.

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South Australia 2016



Adobe stock photo

Overview

In South Australia in September 2016, a once-in-50-years storm, including two tornadoes and an estimated 80,000 lightning strikes, knocked out 22 high-voltage pylons. This kicked off a dramatic drop in system frequency, which in turn prompted generating plants (nine wind farms) to stop exporting energy to the grid due to technical settings that triggered automatic protection mechanisms and disconnection more readily than desirable with voltage disturbances. This led to increased strain on an interconnector (a high-voltage wire importing electricity) from Victoria, which tripped as well, exacerbating the demand-supply imbalance. Ultimately the system operator was forced to disconnect from the National Electricity Market and almost everyone in South Australia lost power. Around 1.7 million people were affected, and for the majority it lasted about six hours. The event itself was not caused by an increased reliance on variable renewable generation, instead it focused attention on a range of emerging challenges the system operator confronted in ensuring security of supply at a time when the resource portfolio was undergoing a rapid transformation. Although some disruption owing to the exceptional weather conditions may have been inevitable, the

episode nevertheless points to the importance of proper regulation and compliance to ensure appropriate technical settings on generation kit.

Demand and supply

In the period immediately before the event in September 2016, the South Australia system, which has a peak gross demand of approximately 3 GW, derived approximately 70% of its energy from wind and solar. An interconnector was importing from Victoria. Demand is not reported as having been exceptional.

The plan and how it failed

In the event of plant failure, the system operator planned to call on voluntary contracts with large industrial consumers to interrupt their supply, and to import more energy through the interconnector. The plan fell apart, however, in a lack of information about the potential extent of generation failure in response to a series of frequency perturbations, such as those caused by the loss of multiple major transmission facilities. This was due to the failure by the owners of several of the wind farms employing technology from a specific vendor, or by the vendor themselves, to inform the system operator

that the turbines were installed with overly conservative under-frequency protective settings.

This was exacerbated by regulatory rules prohibiting the system operator from incurring additional costs to provision the system with increased inertia (by reducing wind output and starting up large thermal plants) in advance of the threat of unusually severe weather.

Dispelling the myths

The day after South Australia lost power, Australian Deputy Prime Minister Barnaby Joyce focused attention on the possibility that the event reflected enhanced vulnerabilities stemming from the nature of renewable energy, stating “obviously we know that South Australia has had a strong desire to become basically all renewable energy and the question has to be asked does this make them more vulnerable.”²² And some linked the blackout to the closure of a South Australian coal power station in May that year, cutting coal out of South Australia’s electricity production equation for the first time.²³

Industry experts, however, suggest coal would have made no difference. Dylan McConnell, Research Fellow — Energy Systems, Climate & Energy College and Energy Transition Hub, said: “If those coal-power stations were still operating, they still would have dropped offline and seen the cascading failure that tripped the generators.

FINANCIAL REVIEW

SA blackout: Nick Xenophon, Barnaby Joyce blame renewables

Having those thermal generations there wouldn’t have helped at all.”²⁴

The primary cause was a combination failure of certain turbine suppliers

to notify the system operator of excessively conservative protective settings, compounded by outdated regulatory constraints — all triggered by an extremely severe weather event and the related, extraordinary failure of transmission infrastructure.

Even so, it may also be noted that Australia’s grid is particularly vulnerable. The National Electricity Market is among the world’s most spread-out interconnected electricity grids — so when there’s a major failure on one line, there are far fewer alternative routes for the electricity to flow. This means power lines are particularly prone to overloading and tripping out, a scenario which is particularly the case in states such as South Australia. As such, some interruption may be expected during truly exceptional weather events.

Lessons

Regulatory reform is key to address the root of the failure, along with enforcement action to incentivise compliance, accompanied by planning to accommodate growing renewables.

In terms of enforcement, in the years that followed the blackout, the Australian Energy Regulator took a number of wind farm operators to court over excessively sensitive protection mechanisms. In the court proceedings, two operators acknowledged that they had not

22 Slezak, M. (2016, 28 September). South Australia’s blackout explained (and no, renewables aren’t to blame). *The Guardian*. <https://www.theguardian.com/australia-news/2016/sep/29/south-australia-blackout-explained-renewables-not-to-blame>

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24 King, A., McConnell, D., Saddler, S., Ison, N., & Dargaville, R. (2016, 29 September). What caused South Australia’s state-wide blackout? *The Conversation*. <https://findanexpert.unimelb.edu.au/news/5934-what-caused-south-australia’s-state-wide-blackout%3F>

gained prior written approval before applying their particular low-voltage ride-through system settings to their generating units.

Regulatory changes have also since been implemented targeting unhelpful turbine settings: had these been in place at the time, the state-wide blackout would likely have been avoided.²⁵

Plans to accommodate growing renewables include a new Australian Energy Market Commission (AEMC) rule that better identifies emerging risks to power system security. The rule

changes the way market operators and network service providers assess the kind of risks that can lead to cascading outages or major supply disruptions in the power system, and requires providers to collaborate with AEMC to ensure the operator has the information it needs to conduct these risk reviews. At the same time, the system operator has focused attention on developing plans and new tools – such as the unlocking of green inertia sources – to support secure operation of the power with very high levels of renewables.

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Overview of good practice and links to relevant event cases

There are common lessons running through each case study. Chief among them is the need for adequate planning to identify the practical challenges system operators face when it comes to ensuring security of supply as the resource portfolio undergoes

rapid transformation towards renewable and distributed resources. Planning must take into account the potential for more extreme weather patterns as a result of climate change. Table 2 presents a summary.

Table 2. Good practice and links to relevant event cases

	Relevant event cases				
	Iberia	Texas	California	Britain	Australia
Updating scenario plans for more extreme weather, drawing on trends evident in more recent available information					
Factoring into plans the impact on demand. Texas, for instance, was an example of a failure to foresee the full impact of extreme cold on electricity demand as consumers turned on inefficient resistive electric heating in poorly insulated housing stock.		✓			
Factoring into plans the impact of extreme weather on supply such as generation capacity and other critical infrastructure. California, for example, illustrated a lack of preparation for the effect of extreme heat on thermal generation capacity.		✓	✓		
Ensuring reliable sources of flexibility are available to maintain grid stability as the resource mix changes					
By significantly increasing commercial arrangements with controllable demand and developing price-responsive demand to meet needs within changing patterns of the renewables resource supply, for example, as in South Australia.			✓	✓	✓
By updating regulations governing the system operator's discretion to take actions in anticipation of potential threats to the grid, including incurring additional cost if necessary, to ensure an adequate supply of grid management tools to maintain grid stability. The system operator in South Australia, for example, was prohibited by regulation from bringing higher-cost resources online as a preventative measure ahead of the storms that brought on the 2016 system blackout.	✓	✓			✓
Requiring embedded resources to remain operational ('ride through') under appropriately wide ranges of system conditions. Britain, for instance, completed retrofits of solar installations with software updates to improve ride-through, and a similar issue most likely contributed to the chain of events that caused the Iberian blackout.	✓			✓	✓
By updating grid codes, interconnection standards and market design to ensure the potential for all grid resources, including inverter-based renewables and batteries, are available to system operators to manage system voltage. In Spain, for instance, virtually none of the installed solar generation was required to contribute to active voltage management, representing a failure to adopt good practice demonstrated in other regions.	✓				
By procuring sufficient system inertia and inertia substitutes to manage system frequency as traditional sources are phased out. South Australia, for example, has since installed four synchronous condensers to increase system inertia without the need for additional thermal generation. They also installed what was the world's first large battery installation to provide, among other services, very fast frequency response.				✓	✓

Table 2. Good practice and links to relevant event cases, continued

	Relevant event cases				
	Iberia	Texas	California	Britain	Australia
Providing strong oversight and 'no excuses' enforcement of grid codes and operating standards					
By adopting sufficiently robust penalties and complementary incentives for performance by grid resources in compliance with codes and contract terms. For instance, multiple resources on the Spanish grid that were expected to contribute to voltage management were operating contrary to their obligations.	✓			✓	✓
For critical resources and the upstream infrastructure on which they rely, including during extreme weather. This would have been particularly helpful in Texas in the case of gas conveying infrastructure. (It is not clear that the new penalties introduced are sufficient.)		✓			
By enforcing full compliance with grid code requirements for operational performance under a range of grid operational scenarios. In South Australia, for instance, all of the wind turbines from a single vendor had been installed with non-compliant protective settings, which the system operator learned only after the 2016 system blackout event.	✓			✓	✓
Aided by greater oversight of embedded generation, including registers of embedded generation capacity, as was enacted in Britain following the 2019 event.				✓	✓
Longer-term investments					
Aggressive deployment of end-use efficiency measures to reduce overall demand. For instance, heat pumps to replace resistive electric heat and improvements in home insulation would be helpful in Texas.		✓	✓		
Updating market design and ancillary services procurement procedures to accommodate investments in batteries and other flexible energy storage where they can deliver comparable or superior performance in support of resource adequacy, grid stability and integration of increased production from variable renewables. Texas, for example, has instituted multiple revisions to ancillary service specifications to enable batteries to participate in procurement.	✓			✓	
Expanding linkages with neighbouring systems to expand options in face of extreme events. South Australia, for example, recently, completed a major expansion of interconnector capacity with the neighbouring New South Wales system.	✓	✓			✓
Reducing impact of events					
Implementation of smart distribution-level technologies and smart pricing to allow the grid operator to minimise disruption by selectively interrupting small groups of customers in sequence for limited periods.		✓			✓
Better sectionalisation of the distribution system to allow more targeted control over what demand gets protected, such as critical infrastructure, and what is available for rotating interruption.		✓			

Common themes and talking points to counter myths after events

- The vast majority of supply loss stems from problems with wires and pipes, most often associated with extreme weather events or natural disaster.
- Renewables don't cause blackouts. Their contribution stems from a failure to adopt and enforce good practices in grid planning, codes and operation.
- The increasingly well-understood challenges for reliable system operation presented by renewables can be readily managed by a competent, well-resourced system operator.
- Regulators and policymakers have a role to ensure regulations and policies support the efficient accommodation of these new technologies, such as making sure generation is not prone to tripping unexpectedly, and unlocking new sources of essential grid services to maintain stable grid operations.
- Climate change is increasing the frequency and severity of extreme weather events and other natural disasters in many regions. As a result, in systems with or without high penetration of renewables, power system regulation, planning and operations need to account for a wider range of weather conditions and more frequent high-impact events.

Annex I – Primer on reliability and resilience

Reliability is (or should be) defined by the interests of consumers (residential, commercial and industrial). The ‘right’ level of reliability balances the value of increased reliability against the cost of achieving it:

- What is the expected cost to consumers of being without electricity given the expected frequency and duration of such an event?
- How much would it cost to be able to expect fewer/shorter interruptions?

Differences in root causes between service interruptions are of no interest to consumers – they’re technical details for ‘the authorities’ to worry about. Yet different standards for reliability have developed separately. Consumers’ experience is reflected in metrics that track the frequency and duration of service interruptions per customer per year from all causes.²⁶ There is often no formal standard, but the data reveal an implicit standard of reliability to which consumers have become accustomed over time. For networks, this typically ranges from tens of minutes to hundreds of minutes per customer per year.

Generation supply, on the other hand, is measured against a standard for the frequency or duration of service interruptions specifically attributable to supply shortfall. The metric most commonly employed stipulates the cumulative ‘hours’ or ‘events’ of interruption, omitting any gauge of the severity of an individual event. Although it is not possible to make a direct comparison between networks and generation supply, the generation supply standard can be conservatively interpreted at a much lower tens of seconds of interruption per customer per year.

There is therefore an obvious mismatch between the generation standard and the standard of

service consumers have come to expect, with the mandated reliability of the generating resources vastly exceeding consumers’ lived experience.

This leads to a misallocation of limited resources between generation and networks, a mismatch that is exacerbated by under-valuation of energy efficiency measures and the innate flexibility of many sources of demand, and by the learned tendency of public media to be less strident about all-too-familiar network-related events (indeed, to be all but oblivious to the commonality of local distribution system events) than about exceedingly rare supply-related events (which in reality occur at a rate far less frequent than even what the standard would dictate). Although there is no reason why the standard of supply reliability should be expected to diminish as more variable resources enter the grid, this historical tendency to overinvest in generation capacity and underinvest in networks and other options will continue to have adverse consequences for consumers. These effects include excess spend through procurement of more generation capacity than required and through an insufficient focus on smart solutions to manage network constraints.

Resilience is a term that is sometimes used in the same context as reliability, but the distinction being drawn (if one is being drawn at all) is not always clear. Resilience becomes a usefully discrete concept when addressing some combination of:

- Ability to resist catastrophic failure of the bulk power grid;

²⁶ These include SAIDI (System Average Interruption Duration Index), the total duration of interruptions for a group of customers, and SAIFI (System Average Interruption Frequency Index), a system index of average frequency of interruptions in power supply.

- Ability to carry on providing at least some services once catastrophic failure has occurred; and
- How quickly the grid can be brought back into something approaching normal operation.

Resilience deals not so much with the reliability of the power grid as it does with issues of emergency planning and response. The ability to carry on providing some services in the event of catastrophic failure is typically a matter to be addressed by governments, whereas reliability is more clearly a matter to be addressed by system operators, albeit subject to applicable public policy.

Conversations about reliability should focus on net consumer benefits. Consumers can little afford the practice of investing in generation margins that offer imperceptible improvements in service reliability when compared to investing in networks; other options would deliver more value for money.

Reliability can also be achieved, at lower cost, by reducing demand through energy-efficiency improvements, and by enabling consumers to benefit from shifting innately flexible consumption to periods when supply is plentiful and cheap. Consumers should be the ultimate arbiters of what constitutes an acceptable and cost-effective standard of reliability.

Annex II – Application of checklist to case study of Texas 2021

This section shows how the checklist can be applied in practice using the case study of the Texan event in February 2021.

a. Demand and supply – what was the background?

- ☐ Demand at the onset of the winter storm event, driven by heavy reliance on resistance heating, was above the extreme winter contingency level, more typical of Texas's demanding summer conditions, and demand peaked at the highest level on record during the event.
- ☐ Supply was initially scarce but sufficient to meet the record demand, but within hours nearly 50% of planned generation failed, mainly gas-fired but also 40% of coal and one of four nuclear units.
- ☐ Wind generates over 20% of Texas's annual supply. Over half of the wind fleet was out of service. But the system operator plans on only about 20% of potential wind production (about 7 GW) under severe winter conditions. In this event, the fleet operated on average at a bit more than 10% of potential (about 4 GW), so below plan, but a small contributing factor.
- ☐ Unlike other regions of North America, Texas's grid is effectively an island, electrically isolated from neighbouring systems for historical reasons. As a result, there is limited ability to mitigate events by broadening the supply solutions. That said, as the crisis affected a broad swathe of the midcontinent it is unclear just how much help would have been available.

b. What appears to be the root cause(s) based on best available information?

- ☐ The event was precipitated by a winter storm of historically rare, but not unprecedented, depth and duration. The weather drove demand to unforeseen levels, and some amount of rolling interruption over a few hours would likely have been necessary in the best case. In the event, the rapid failure of nearly 50% of planned generation early in the hours of 15 February, overwhelmingly gas-fired generation, brought the system within minutes of collapse. The plant failures were caused by a combination of inadequate freeze protection at the plants themselves and in the fuel supply infrastructure on which they rely. Regional gas production fell by about 50% before beginning to recover. This was all largely unforeseen. Reliance on wind generation was not a major factor.

c. What is the relative severity of the event?

- ☐ This was an extremely serious event. More than 4.5 million customers lost power, many for three days or more. The severe conditions, in a region heavily reliant on resistance electric heat, led to more than 200 deaths and billions of dollars in property damage.

d. What was the system operator's resource plan for meeting demand under the relevant circumstances (assuming there was one)?

- ☐ Demand exceeded the system operator's extreme winter planning scenario. Available resources at the onset of the storm were roughly in line with that

scenario and were stretched to the limit to meet demand. Around 90% of planned generation was fossil and nuclear, three-quarters of that being natural gas. While the system operator would likely have had to resort to some level of rolling interruptions for a few hours as the storm continued through the week, they would probably have averted any truly dire consequences had the generation fleet held up as planned. In the event, of course, that did not happen.

e. What was the expected role for renewables in the relevant contingency plan?

- ☐ The plan called for about 7GW (out of installed capacity of 32GW) of wind generation to meet 67GW of demand, so about 11% of total resources.

f. To what extent did the system operator plan for and deploy demand flexibility?

- ☐ It is not clear how much of the approximately 20 GW of ‘unserved demand’ was voluntary. Wholesale prices famously hit the cap of \$9,000/MWh and stayed there for several days, but penetration of dynamic retail pricing was limited and metering infrastructure was not up to best-in-class standards. A different form of flexibility – the ability to selectively interrupt small groups of customers in sequence for limited periods to minimise disruption – was drastically limited by distribution system architecture that placed large amounts of load off-limits to protect specific critical customers. As a result, millions of customers were without power for days while millions of others never lost power at all.

g. How exactly did the PLAN fail – what was supposed to have happened that did not (NOT what renewables didn’t do that they weren’t expected to do)?

- ☐ Thermal generation – that was reasonably expected to operate – failed, largely because of poor plant weatherisation and its reliance on natural gas infrastructure that was far more vulnerable to severe winter weather than either the system operator or the regulator anticipated. Most of the wind fleet was also frozen, and that’s an issue for the future, but that was largely expected and accommodated for in plans.

h. What false claims are being promoted by fossil industry players and their enablers?

- ☐ Fossil industry actors, including the state’s natural gas regulator, were quick to point to Texas’s rapid uptake of wind over the past 20 years and the large amount of wind generation that was offline at the time – about 18 GW of the 32 GW installed. The narrative bounced between Texas’s wind fleet’s vulnerability to freezing and the effect of low wind speeds during cold winter weather on the dispatchability of wind.

i. Why exactly are the claims false?

- ☐ The fact that the system operator’s plan accounted for both of these factors – frozen wind capacity and low wind speeds during cold winter weather – and that they therefore had little to do with why the disaster occurred, went conveniently unmentioned. The claims are a familiar mix of factual snippets removed from context, woven into an intentional misrepresentation. One difference in this case compared to other examples, unfortunately, is that the event was legitimately catastrophic, contributing to many deaths.

j. What are the legitimate transition-related challenges manifested in the event?

- ☐ The continued reliance on fossil fuels in the system operator's plan to deal with these circumstances is unsatisfactory. The fact that the Texas renewables resource at the time, nearly all wind, is so reliably unreliable under these circumstances is also unsatisfactory. The lack of resource diversification and storage has improved with the rapid uptake in solar and batteries in the years since. Flexible demand was and is under-developed, in Texas and elsewhere. Strong interconnection with neighbouring regions is best practice; this remains a vulnerability for Texas.

k. What best practices could a prudent system operator have deployed to avoid the event?

- ☐ Better scenario planning based on available historical information.
- ☐ Stronger oversight and 'no excuses' enforcement of operational standards for critical resources, including the upstream infrastructure on which they rely.
- ☐ Planned, accelerated reduction of dependence on fossil fuels.
- ☐ Aggressive deployment of building efficiency investments, smart distribution-level technologies and smart pricing to access the value of flexible loads.
- ☐ Better sectionalization of the distribution system to allow finer control over what gets protected and what is available for rotating interruption.
- ☐ Increase the Texas grid's linkages with neighbouring systems to expand options for dampening the impacts of such events in future.

Annex III – Glossary

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- **Alternating current** – the grid operates on a current which periodically reverses direction and changes its magnitude continuously with time. 
- **Asynchronous resources** – resources that do not rotate at a frequency compatible with the frequency of the alternating current (see Inverter-based resources). 
- **Blackout** – total collapse of the grid. 
- **Dispatchable** – resources whose energy production or consumption can be controlled and changed according to the needs of the system. 
- **Embedded generation** – electricity production capacity connected to a distribution rather than transmission network. 
- **Flexibility** – describes the degree to which a power system can adjust the electricity demand or generation in reaction to both anticipated and unanticipated variability. 
- **Grid codes** – specifications set by system operators, with approval of regulators, for devices desiring to connect to the grid. The purpose of the codes is to preserve safe and reliable system operation. 
- **Grid stability** – the maintenance from one moment to the next of system frequency and voltage within narrowly prescribed ranges, essential to preventing damage to equipment connected to the grid. 
- **Inertia** – a service that slows the rate of decline in system frequency following a sudden disruption. Inertia has traditionally been supplied by the rotating mass of synchronous generators and large motors connected to the grid. Increasingly, very fast-responding storage devices or inverter-based resources can provide ‘synthetic’ or ‘virtual’ inertia to react to imbalances. 
- **Inverter-based resources** – resources that do not rotate, or that rotate at a frequency incompatible with the grid and therefore must be connected via solid-state electronic devices called inverters. 
- **Reactive power** – the power ‘lost’ to end users due to the extent to which the alternation of current is pushed out of synch with the alternation of voltage. 
- **Reliability** – reflects the extent of interruption to services. A prudent level of reliability trades off the expected cost to being without electricity against the cost of reducing expected interruptions. 
- **Resilience** – relates to abilities to resist catastrophic failure of the bulk power grid, to carry on providing at least some services once catastrophic failure has occurred, and to quickly bring the grid back to normal operation. 
- **Rotating/rolling service interruption** – when the system operator selectively orders groups of customers to be interrupted for limited periods of time in sequence while also protecting designated critical loads and ensuring operability of the grid. 
- **Short-circuit ratio** – the ability of a grid resource to counter local drops in voltage due to a fault by rapidly injecting an oversupply of current and reactive power at the point of interconnection. 
- **Synchronous resources** – machines that rotate at a frequency compatible with the frequency of the alternating current. 
- **System frequency** – reflects how frequently the direction of current alternates on the grid. Most things connected to the grid are designed to operate safely based on a defined expected range of system frequency. 
- **System operator** – the designated ‘traffic cop’ of the electricity highway, to ensure that demand and supply are balanced and grid stability is maintained in real time. 
- **System voltage** – the magnitude of the force with which current is driven across the network. 



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