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A Wake-Up Call for the Utility industry: Extreme Weather and Fundamental Lessons from 2021

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ABSTRACT

We have examined the critical extreme weather events of 2021 that resulted in disruptions of normal power system operations, the loss of life, and multibillion dollar losses to the US economy. These impacts occurred due to extreme cold, extreme heat, drought, slower post-landfall dissipation of hurricanes, and more intense large-scale thunderstorm systems. We point to the causes but also argue for the changes in planning and operations required to be prepared for and have responses to these events. Specifically, we focus on recognizing the reality of extreme events and planning for their increasing frequency, intensity, duration, and geographic scope; modifying resource planning and adequacy metrics to incorporate common mode events; enabling the power system to depend on reliable natural gas fuel supplies; redesigning power markets to better compensate resources and flexible demand for reducing the probability of outages; and developing resilient systems.

1. Introduction

The tragic consequences of the February 2021 Texas blackout; the extreme heat wave of June 2021 in the Pacific Northwest; the worst drought in the last 1,200 years that is reducing water supplies and igniting forest fires across much of the West; the intensity and slower post-landfall dissipation of tropical storms such as Hurricane Ida that knocked out the transmission lines serving New Orleans before leaving 232,000 customers without power and killing 56 people in five Northeastern states in August 2021; and the intensity of large-scale thunderstorms across the center of the country such as the December 2021 derecho, with its 100 mph straight line winds and 120 tornados, that left 600,000 without power should have served as a wake-up call for the US utility industry to restructure their planning for resource adequacy and resilience, but that appears not to be the case. Such high impact events are no longer infrequent.

This paper presents a summary of what has occurred over the last year, the impacts on the power system of the increase in extreme weather events, and a detailed analysis of solutions. The authors approach this problem based on their background in power systems, energy market design and analysis, utility regulation, and probabilistic weather forecasting and evaluate strategies for how U.S. energy systems can adapt to the increasing frequency, intensity, duration, and geographic scope of the extreme weather and common mode events that simultaneously reduce the availability of multiple resources and increase demand.

While it can be important to look back to ask what might have been avoided, hindsight is insufficient. The paper summarizes recent extreme weather events and their impacts for the purpose of focusing attention on lessons for the future.

2. Extreme Weather 2021

The Texas blackout from Winter Storm Uri provides a dramatic example of the failure of energy systems to recognize the risk, plan for, and manage the impacts of a weather-related disruption of normal operations. During the period from February 8 to 20, 2021, unusually cold weather impacted a wide area of the south-central United States. In Texas, the electric and natural gas systems failed with tragic consequences. To maintain bulk power system reliability, grid operators were forced to shed 23.4 GW of firm load, including 20 GW in the Electric Reliability Council of Texas (ERCOT) at the worst point in the event. From 7:00 a.m. on February 15 to 1:00 p.m. on February 17, ERCOT averaged 34 GW of generation outages, a quantity equal to nearly half of the system's all-time winter peak demand. Most of the unplanned outages were at gas-fired generators. Outages and derates of wind, coal, nuclear, and solar generation also increased. ERCOT's largest estimated resource deficiency, 28.3 GW, occurred on the

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morning of February 16, when it was experiencing 26.2 GW of forced outages at thermal (gas, coal, nuclear, and biomass) generators, 2.5 times the worst case assumed in ERCOT's Seasonal Assessment of Resource Adequacy.[1] Natural gas production in Texas and the south-central U.S. declined by more than 70% and throughput at gas processing plants fell by more than 80%, compared to earlier in the month.

The electric and gas systems are interdependent: the loss of power to natural gas infrastructure resulted in power line outages and firm load shedding that caused a 23.5% of the decline in natural gas production.[2] The cold weather also increased demand above the seasonal forecasts and prior winter peaks. In ERCOT, a new winter peak demand of 69,871 MW was set on the evening of February 14.

Grid frequency rapidly declined in the early hours of February 15.[3] As system frequency approached 59.3 Hz, ERCOT began ordering firm load shedding. At one point "operators had only nine minutes to prevent approximately 17,000 MW of generating units from tripping which could potentially cause a complete blackout of the ERCOT Interconnection."[4] Utilities had limited options. More than 4.5 million customers were left without electricity, some for as long as 4 days, in below freezing temperatures from February 15 to 18.[5]

The Texas Department of State Health Services attributed 210 deaths to the Winter Storm Uri, while independent experts identified an estimated 700 excess deaths during the storm and resulting power outages.[6]

The financial costs of the 2021 Texas power outage were in the billions of dollars and orders of magnitude larger than the costs of ERCOT's winter weather service interruptions in 1989 and 2011.[7]

Winter Storm Uri was notable for its intensity, duration, and geographic scope. The National Weather Service issued Winter Storm Warnings for the entire states of Texas, Oklahoma, and Arkansas, virtually all of Louisiana, Mississippi, and Kentucky, and most of New Mexico, Tennessee, Indiana, and Ohio.

While Winter Storm Uri was larger and more intense than prior winter storms, this type of event may reoccur. It was an example of a "disrupted polar vortex", a weakening and southerly excursion of the high-altitude winds that brought cold temperatures into a mid-latitude region. Some researchers have linked warming in the Arctic to disruptions in the jet stream that causes extreme cold events in Asia and North America.[8] This disruption was the main driver of cold events seen in 2011, 2014, 2018, and 2021.

3. Other Extreme Weather events are increasing as well

Heat waves are occurring with greater frequency and intensity,[9] duration, and spatial coverage. Large heat waves that simultaneously affect multiple areas have become 6 times more frequent, 46% larger, have increased in intensity by 17% since 1979.[10] Heat waves stress power systems by increasing the demand for power, negatively impacting thermal generators, and overheat power lines and distribution transformers. As the geographic scope and duration of contemporaneous heat waves increase the ability share resources between regions also declines. High heat events, such as the 2021 Pacific Northwest heat wave, also have been amplified by changes in the jet stream. With a slowing of the jet stream, a heat dome settled over the Pacific Northwest in June, increasing temperatures in Seattle to 109°, Portland to 116° and towns in Eastern Washington and British Columbia to over 120°F; with an attributed 400 excess deaths.

Heat has other compounding impacts. Droughts are increasing in intensity, duration, and spatial coverage.[11] The western United States is enduring a 22 year long drought that is one of the worst to impact the region in the last 1,200 years.[12] Extreme or severe drought conditions impacted nearly 90% of the Western U.S. in 2021. The drought is dramatically shrinking the reservoirs behind Colorado River dams and reduced hydroelectric generation in California by 38%.[13] It is reducing the availability of cooling water for power plants across most of the WECC and ERCOT regions. Moreover, the drought is curtailing water supplies for agriculture and domestic use. This in turn may lead to increased power demand for water pumping and new desalination facilities.

Wildfires have increased in intensity, duration, and spatial coverage. The annual average acreage consumed by large wildfires in the U.S. in the period

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[1] King, Rhodes, Zamikau, and Lin 2021.

[2] *Ibid.*

[3] Magness. 2021.

[4] FERC and NERC 2021.

[5] FERC and NERC 2021; see also: Wood et al. 2021.

[6] Aldhous, Lee, and Hirji 2021.

[7] Golding, Kumar and Mertens 2021; and King, Rhodes, Zamikau, and Lin 2021.

[8] Cohen et al. 2021.

[9] IPCC 2021.

[10] Rogers et al. 2021.

[11] IPCC 2021 : SPM-11.

[12] Williams et al. 2020.

[13] Gearino 2021.

1987 to 2003 was more than six and a half times the annual average area burned in the period 1970 to 1986.[14] Moreover, the average area burned each year between 2004 and 2020 was nearly double the average from 1987 to 2003.[15] The upward trend has continued with the average area burned over the past five years 26% higher than in the prior five-year period and more than double the area in the 1990s.[16, 17, 18] Wildfire risk has required deenergizing transmission lines in fire prone areas and threatened the loss of major lines.[19] In 2021, Oregon's Bootleg Fire threatened to interrupt the intertie bringing 5,500 MW of power from the Pacific Northwest into California.[20] The de-energizing of power lines by PG&E to lower fire risks in 2019 led to 12 million person-days of power interruptions.[21] Additionally, in September 2020, smoke from wildfires reduced solar generation in California by nearly 30%.[22] Wildfire smoke also contributes to unhealthy levels of airborne fine particulates and causes an estimated 1,500 to 2,500 short-term and 8,700 to 32,000 long-term premature deaths per year.[23]

The intensity of Atlantic hurricanes is increasing.[24] Moreover, a reduction in the rate of post landfall decay in storm intensity has subjected larger areas to intense winds and heavy rainfall, resulting in a consequently larger economic toll.[25] For example, Hurricane Ida took out the transmission lines that serve New Orleans cutting power to more than one-million customers with some experiencing outages of up to sixteen days. Ida then turned north and brought down power lines, flooded streets and basement apartments, interrupted service to 232,000 customers, and killed 56 people in in five Northeastern states.[26]

4. Damage estimates from Extreme Weather

Since 2008, the most frequent high impact - $1billion damage - weather events have been non-tropical severe storms. These extreme precipitation and wind events are becoming more intense and frequent. They include the large formations of thunderstorms, known as mesoscale convective systems, which occur frequently in the central and southeastern U.S. These storms can produce heavy precipitation, flash floods, severe winds, and derechos – intense straight-line winds – and occasional tornedos.[27, 28] For example, in August 2021, storms dropped 17 inches of rain in parts of Tennessee, which produced widespread flooding killing 22 people. A December 2021 derecho impacted six states from Colorado and Kansas to Wisconsin, produced straight line winds in excess of 100 mph and 120 tornados, and left 600,000 customers without power. A similar August 2020 derecho, which formed in South Dakota and Nebraska, unleashed high winds, peaking at over 110 mph, across a 90,000 square mile area that was home to more than 20 million people. The line of thunderstorms moved through Iowa, and parts of Illinois, Wisconsin, Indiana, and Michigan and caused more than $11 billion in damages in a single day. It left 1.9 million customers without power, some for as long as two weeks. Preliminary research suggests these conditions also can produce more frequent and intense tornados, such as the unusual December 2021 tornado cluster that killed 77 people in Kentucky.[29] The increasing impact of severe storms is reflected in average outage durations including major event days (SAIDI with MED), which have been available from U.S. EIA since 2013. The average annual duration of outages for utilities that reported based on IEEE standards increased from the period of 2013 through 2016 to the years 2017 through 2020 by 70%.[30]

The increasing number and impacts of extreme weather events are illustrated in Figure 1. The average number of U.S. Weather Events causing over $1B in damages has increased from 2.9 per year in the 1980s to 17.2 such events per year over the last five years. The average annual cost of these billion-dollar events has increased from $17.8 billion in the 1980s to $148.4 billion per year in the last five years. Much of the trend is clearly attributable to an increase in extreme weather events, although some portion of the change in costs may be due to demographics.

Figure 1: United States Billion-Dollar Disaster Events 1980 – 2021 (CPI-Adjusted)[31]

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[14] Westerling et al. 2006.

[15] U.S. EPA 2022.

[16] Ibid.

[17] Patel 2018.

[18] Union of Concerned Scientists 2020.

[19] CAISO 2020.

[20] Mulkern 2021.

[21] Abatzoglou et. at. 2020.

[22] U.S. EIA 2020.

[23] Fan et al. 2018.

[24] IPCC 2021: SPM-11.

[25] Li and Chakraborty 2020.

[26] U.S. EIA 2021.

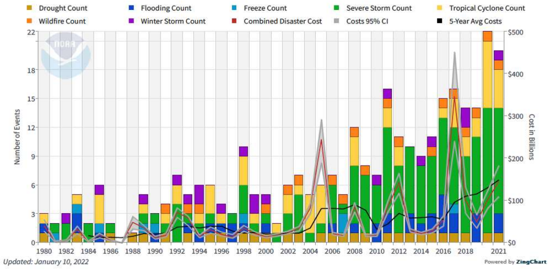
[27] Schumacher and Rasmussen 2020.

[28] IPCC 2021: SPM-10.

[29] Lepore et al. 2021.

[30] U.S. EIA 2014 – 2021.

[31] NOAA 2022.



Despite the recent impacts on power systems, the consequences of failing to recognize and mitigate climate risks, and research characterizing potential impacts of climate change on energy systems, the extent to which the impacts of climate change and extreme weather have been incorporated into system planning and operations remains limited. Many utility planners continue to rely on historical data without considering climate models or planning for events that may be outside of or have rarely occurred in the historical data.

The increasing frequency with which extreme weather is impacting the power system and the results of climate models suggest these impacts are likely to intensify. From this experience we can derive fundamental requirements that include:

1. Resource and reliability planning should address region-specific risks of extreme weather.
2. When forecasting the probability of extreme weather events, planners should both account for the trends and rate of change in the frequency, intensity, duration, and geographic scope of adverse weather patterns and consider the possibility of events well outside of historical experience.
3. Planners and operators should seek to make the range of risks and potential outcomes transparent to relevant decision makers. The probability of extreme events can be assessed with current and evolving weather forecasting methodologies.
4. Extreme events and common mode failures are often not limited to a single sector. Planners, operators, and policy makers will need to ensure cross sector coordination between the power sector and other interdependent elements of critical infrastructure, particularly when events will have large customer and societal costs.

These basic requirements will impact multiple areas of energy system planning and operations including the definition of key performance metrics, resource adequacy and grid planning, ensuring fuel supply reliability, power market design, resilience planning and the management of events that disrupt normal system operations.

5. Resource Adequacy and Grid Planning that reflects the Risk of Extreme Events

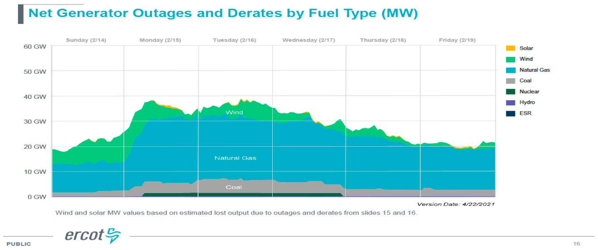
Today's planning for resource adequacy is about relatively common, known, and anticipated types of events. Planners tend to focus on annual or at most seasonal worst-case scenarios for load (highest demand day) as they plan for system adequacy. The results are based on expected values based on historical data with only limited weight given to high impact events that have historically been infrequent and for which we have limited historical data upon which to base statistical analyses. Too little time has been spent focused on the tails of the event distribution and even less on the risks associated with common mode events. Climate models and the trend of increasingly frequent and severe extreme weather are often ignored or treated as too uncertain to include in planning. Incorporating climate forecasts and trends in planning will require planners, involved stakeholders, and utility regulators to develop a better understanding of climate models and relevant data.

The most significant failing of today's resource planning analytics is the lack of appropriate metrics to measure both preparedness and the cost of failure. By analyzing and characterizing the probability of different common mode events along with supply intermittency, the industry can develop risk metrics and plan for and become increasingly resilient in its response to extreme events. Historically, the industry has focused its attention on engineering analytic metrics. The concept of reliability measured as failure "one day in 10 years" has no meaning in terms of the cost to consumers nor the benefits when they exist. The change needed is from engineering values to values associated with the cost to consumers whether measured in Value of Lost Load or in probability metrics that incorporate severity of event, and the geographic extent of event along with the risk economic loss. These measures all require stochastic analytic techniques that either exist or are under development, but which require significant reorientation of planners and planning if we are to move forward to a probabilistic approach to resource adequacy.

Today's power industry employs minimal stochastic planning metrics and methods and as a result tends to understate the probability of supply disruptions affecting multiple units and their impact on consumers and the system itself. This is the reality across topics varying from weather to fuel supply and cyber security. The industry is, however, moving into a new era in which generation portfolios are changing, a larger proportion of generating assets are intermittent renewable resources, generation occurs behind as well as in front of the meter, the carbon content of their energy supplies is rapidly evolving, and the economy has become increasingly dependent on a reliable supply of electricity. All these changes increase the need for stochastic methods and metrics of planning for resource adequacy that are more customer focused and resilience focused.

The events of February 2021 in ERCOT illustrate the fundamental weakness of conventional reliability planning metrics and methods. In November 2020 ERCOT stated that for the winter of 2020-2021: "We studied a range of potential risks under both normal and extreme conditions and believe there is sufficient generation to adequately serve our customers."[32] The assessment proved to be very wrong for several reasons. First, the "Range of Potential Risks" included only three sensitivity cases. Second, in specifying these cases, planners failed to consider the possibility that Extreme Peak Demand and Extreme unit Outages might coincide with Low Wind Output. Third, each of the input sensitivities was based on a limited range of historical data for the given parameter, which was unrepresentative of the future and in this case understated the conditions observed in February 2021. Additionally, ERCOT does not appear to have considered how severe weather could impact gas supplies, which became a large common mode failure that resulted in massive load shedding. Further, ERCOT has a large base of wind resources (31.4 GW nameplate REC/NERC). During February 14 and 15, 2021, because of a common mode failure, up to 18.3 GW (nameplate) were offline or derated (UT Austin), though actual energy loss was smaller than lost MW capacity because wind farms do not operate at full output during most hours. Hourly expected lost generation by type from February 14-19 is shown in Figure 2.

Figure 2:



6. Effective integration of Risk into Extreme Weather Market Prices

Since the late 1990's there has been an increased awareness of the need for market forces to play a significant role in the planning and operation of the power industry. The restructuring of the industry moved the focus of resource investment away from the traditionally regulated, vertically integrated utility to private investment by independent producers. This trend has continued and intensified with the recognition that the future of the industry is in clean, renewable generation, virtually all of which is provided by non-utility planned, developed, and owned wind and solar (and now increasingly, storage). The role that the market is playing is only tangentially taken into consideration in the resource adequacy planning process through the existence of administratively specified capacity auctions where they exist. Only the ERCOT operating reserve demand curve (ORDC) methodology provides a clear connectivity between scarcity (probability of inadequacy) and the value of operating resources. As was seen in February in ERCOT, ORDC initially functioned as intended sending electric energy prices to their maximum level of $9000 per MWh. The signal was dramatic, those generators online were able to reap the benefits as designed. Consumers responded to the high prices by reducing demand. The high prices were not well accepted by Texas consumers or suppliers caught without gas supplies or wind resources. The economic signals, while correct given the design of the ERCOT market, create a level of volatility, uncertainty, and risk that investors must price into their analysis of potential investments.

Consumers are looking to the electric market to provide a reliable (and resilient) product at a reasonable price. Investors are looking to identify assets located in markets where outcomes, even if uncertain as a function of, for instance, weather, are none the less statistically forecastable and not unduly volatile if they are to provide a cost-effective product. The challenge of the market is to be able to identify the value of reliability (resource adequacy) on a continuous basis rather than only episodically. We recognize through Locational Marginal Pricing (LMP) that the cost to provide, therefore the value to consume electricity varies with time and locations. The same concept exists for the value of resource adequacy, i.e., consumers should pay for adequacy as a function of the value they place on the basic product, electricity. Suppliers should be paid for their contribution to provision of adequacy. This creates a market of willing buyers and sellers at an agreed price. The question is how to arrive at that price both in time and space (as in LMP).

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[32] ERCOT. 2020. *Final Seasonal Assessment of Resource Adequacy for the ERCOT Region (SARA) Winter 2020/2021.* (*https://www.ercot.com/files/docs/2020/11/05/SARA-FinalWinter2020-2021.xlsx*)

A U.S. Department of Energy, ARPA-E PERFORM project on Stochastic Nodal Adequacy Pricing (SNAP) has developed a modeling platform that stochastically forecasts the probability of resource inadequacy based on the development of a large number of probabilistic hourly forecasts of weather and electric system operations over the next several days (the prediction horizon). Given the unresolved weather uncertainty over the prediction horizon, probabilistic forecasts use the most information practically available at the time of the forecast. Modeled system operational uncertainties include random generation and transmission outages, that might occur over the prediction horizon and could be random and independent of weather conditions or be weather driven.

SNAP combines advanced atmospheric science with modern electrical engineering, optimization, and high performance computing to compute locationally distributed hourly probabilistic measures of system inadequacy for the prediction horizon. These measures can then be transformed into Stochastic Nodal Adequacy Prices (SNAPs) akin to LMPs that are both nodal and temporal to be paid to suppliers and charged to consumers.33 SNAP differs from both Operating Reserve Demand Curves (e.g., ERCOT and PJM) and Staff's proposed scarcity price functions in that it continuously calculates the forward-looking statistical probability of inadequacy for a given hour and location and updates prices on a day-ahead or more frequent basis as opposed to utilizing fixed scarcity functions that are not grounded in market fundamentals, do not fully reflect the physical and engineering state of the system, and provide less accurate representations of risk. This stochastic approach is designed to provide investors consistent and predictable compensation based on their contributions to reducing reliability risks.34 Moreover, charging customers stochastic nodal adequacy prices along with energy prices gives customers the opportunity to respond to changing time- and location-specific reliability risks. SNAP pricing provides investors, project developers and consumers alike a much more precise and powerful economic signal than rigid capacity prices or largely inaccurate ORDC-based scarcity payments.

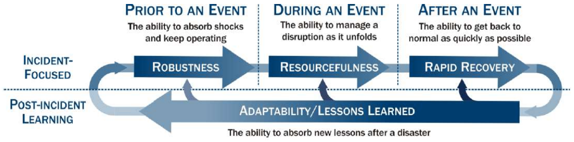
For the supplier of energy, the SNAP methodology provides a statistically calculable probability of revenue and its variability. For the consumer it provides an opportunity to choose and be charged for the level or reliability that meets their needs.

7. Creating Resilient Systems

Increasingly frequent extreme weather events, interruptions of gas supplies for power generation, multi-day periods of limited wind and sunlight in systems that rely on renewable resources, and cyber-physical attacks are common mode events that can produce long-duration, widespread disruptions in the provision of electric power and other critical services. The scope and scale of the impacts requires greater attention to system resilience.

FERC and the National Infrastructure Advisory Council (NIAC) have defined resilience as, "The ability to withstand and reduce the magnitude and/or duration of disruptive events, which includes the capability to anticipate, absorb, adapt to, and/or rapidly recover from such an event."[35] The NIAC provided a framework for evaluating the resilience of critical infrastructures, illustrated in the diagram below.[36]

Figure 3: NIAC Resilience Construct



Others have proposed similar multi-part frameworks to describe resilient infrastructures and power systems that can absorb, adapt, and recover from the impact of disruptive events.[37]

In the context of common mode events, resilience is not simply a function of hardening or adding redundant assets. A power system also can become more resilient by avoiding reliance on difficult to replace single points of failure and developing the capability to isolate faults, reroute power around failed components, offer basic levels of service on islanded circuits, and maintain power to critical facilities. Resilient systems can innovate during an event by redeploying existing resources, for example, using electric school buses as mobile power stations.[38] They

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[33] In the original work of Schweppe et al Spot Pricing of Electricity (Kluwer 1989) this concept was referred to as the Quality of Supply component that was added to the marginal nodal cost of energy to reflect the value to consumers of reliability.

[34] 2022 IEEE Power & Energy society General Meeting, "Tabors, R and Rudkevich A "Stochastic Nodal Adequacy Pricing (SNAP) Spot Pricing of Reliability," Denver, CO July 2022. eCF Paper Id: 22PESGM3856-ZyMruyPaL

[35] FERC 2018; NIAC 2010.

[36] NIAC 2010.

[37] Flynn 2008; Francis and Bekera 2014; Panteli, Trakas, Mancarella, and Hatziargyriou 2017; Kemabonta, and Mowry. 2021; Kemabonta 2021.

[38] Shahan 2020.

will value flexibility. Given an intelligent control system, a backup generator or battery storage unit might help maintain service to a critical facility or on an islanded circuit during the event and later assist in reenergizing adjacent portions of the grid.

The National Academies' Committee on Enhancing the Resilience of the Nation's Electric Power Transmission and Distribution System identified the key distinction between reliability and resilience, finding that, "Resilience is not the same as reliability. While minimizing the likelihood of large-area, long-duration outages is important, a resilient system is one that acknowledges that such outages can occur, prepares to deal with them, minimizes their impact when they occur, is able to restore service quickly, and draws lessons from the experience to improve performance in the future."[39]

Resilience ideally would be measured from the customer's perspective, considering customer costs and societal impacts. EPRI has been developing a framework for evaluating the physical and financial consequences of extended outages to determine how customers value resilience and monetize the resilience value of utility investments.[40] Additional research is needed to evaluate how customer and societal costs change in widespread, long-duration outages.

In response to Presidential Policy Directive 21 on *Critical Infrastructure Security and Resilience* (February 12, 2013), Sandia National Laboratories recommended a risk-based framework reflecting disturbance(s) or threat(s) and their consequences in terms of social effects and system performance. It proposed developing resilience metrics represented as probability density functions of consequences that may result from one or more threats.[41] The development of probability density functions and economic valuations for the risk of outages would represent a fundamental shift from NERC's existing resource adequacy criteria that focus on expected values and do not include customer or societal costs.[42]

In reviewing utility integrated resource plans (IRPs) and ISOs/RTOs supply planning, we have found very only limited consideration of common mode events beyond concerns about fuel supply. Individual utilities such as Commonwealth Edison and states such as California have considered or are requesting that utilities consider common mode events in their resource adequacy calculations. Resilience is occasionally mentioned and included as a qualitative metric, such as reliance on markets for energy and capacity,[43] or fuel diversity. ISOs/RTOs that have capacity markets have made adjustments in recent years to require gas-fired plants with a capacity responsibility also have firm gas or a short-term alternative fuel supply. Also, in the three northeastern ISOs, capacity delivery requirements have been extended to the winter.

ISOs/RTOs reported their resilience concerns in FERC's grid reliability and resilience pricing docket (AD18-7). The concerns reported largely reflected geographic differences. Four RTO's reported gas related concerns; SPP reported concerns about coordinating large amounts of renewable resources; and California ISO reported concerns related to fire, earthquakes, drought, and changing weather conditions.[44] Some of these concerns extend to issues outside the RTO's scope of operations.

Resilience requires a broad systems approach to plan and prepare for addressing region-specific risks. Planning should identify and prioritize services that are critical to the maintaining public health, safety, and the basic functioning of the community. Planning should involve relevant government authorities and providers of other critical services and reflect community input.[45] Critical services may not be limited police, fire, hospitals, and communications. For example, community cooling centers can play a critical role in minimizing the health impacts of a prolonged heat wave. A power outage that coincides with a heatwave in an urban area could leave hundreds of thousands exposed to dangerous temperatures. Although many cities designate cooling centers for those without air conditioning, such centers often have the capacity to serve less than 2% of a city's population and may not have backup power supplies.[46]

Developing a more resilient power system may start by creating microgrids or using distributed energy resources to maintain power at a range of critical facilities. However, adapting to a changing climate may require more fundamental changes in the structure and operation of power systems. With the knowledge that extreme weather will periodically degrade the power system, the system architecture may need to evolve into a layered system with defined relationships between bulk power, distribution, and smaller circuit level segments; fractal zones that both balance supply and demand in an islanded mode and can participate in the larger grid; and autonomous operations that combine distributed control and locational pricing to balance variations in demand and resource availability both locally and when interconnected to the larger grid.[47]

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[39] National Academies of Sciences, Engineering, and Medicine 2017.

[40] Roark 2018; Ela, Entriken, Hytowitz, Singhvi, and Vittal. 2020

[41] Watson, et al. 2014.

[42] *Ibid.*

[43] Indianapolis Power and Light 2016.

[44] Hytowitz et al. 2019.

[45] McAllister 2015; McAllister 2015a.

[46] Flavelle 2021.

[47] Kroposki et al. 2020; Miller et al. 2014.

8. Looking forward to Summer and beyond conditions in 2022

The NERC 2022 Summer Reliability Assessment presents a mixed but generally harsh forecast of summer conditions particularly in the Midwest and West.

- "Midcontinent ISO (MISO) faces a capacity shortfall in its North and Central areas, resulting in high risk of energy emergencies during peak summer conditions
- "Drought conditions create heightened reliability risk for the summer.
  - "Energy output from hydro generators throughout most of the Western United States is being affected by widespread drought and below-normal snowpack
  - "Extreme drought across much of Texas can produce weather conditions that are favorable to prolonged, wide-area heat events and extreme peak electricity demand.
  - "As drought conditions continue over the Missouri River Basin, output from thermal generators that use the Missouri River for cooling in Southwest Power Pool (SPP) may be affected in summer months.
- "All other areas have sufficient resources to manage normal summer peak demand and are at low risk of energy shortfalls from more extreme demand or generation outage conditions."[48]

By contrast, the popular press (CNN) in June of 2022 has challenged the conclusion that "all other areas have sufficient resources…"

"As heat ramps up ahead of what forecasters say will be a hotter than normal summer, electricity experts and officials are warning that states may not have enough power to meet demand in the coming months. And many of the nation's grid operators are also not taking climate change into account in their planning, even as extreme weather becomes more frequent and more severe.

"All of this suggests that more power outages are on the way, not only this summer but in the coming years as well.

"Power operators in the Central US, in their summer readiness report, have already predicted "insufficient firm resources to cover summer peak forecasts." That assessment accounted for historical weather and the latest NOAA outlook that projects for more extreme weather this summer.

"But energy experts tell CNN that some power grid operators are not considering how the climate crisis is changing our weather — including more frequent extreme events — and that is a problem if the intent is to build a reliable power grid.

"The reality is the electricity system is old and a lot of the infrastructure was built before we started thinking about climate change," said Romany Webb, a researcher at Columbia University's Sabin Center for Climate Change Law. "It's not designed to withstand the impacts of climate change."[49]

9. Conclusions

Extreme Weather is a challenge that has yet to be effectively addressed by the electric power industry as it looks to assure resource adequacy at times of system stress, independent of when those periods may occur throughout the year.

While there are no simple answers, the conclusions of the authors are that:

- The industry must plan for the reality of increased frequency, intensity, duration, and geographic scope of extreme weather events. Those responsible for resource adequacy will need to address region-specific risks of extreme weather, including events outside of historical experience; use long-range scenario planning and short-term probabilistic forecasts; and take steps to manage and mitigate potential adverse impacts.
- The industry will further need to modify the way it undertakes the process of resource planning and considers the adequacy metrics that it uses to incorporate common mode events. The events themselves (and the renewable resource output that will make up a greater proportion of physical assets) are stochastic. This will require the development of stochastic planning methods and resource adequacy metrics that are based on customer costs, incorporate the risk of common mode events, and focus attention on how to avoid or mitigate the cost of adverse events should they materialize.
- Today, and for the near-term future, the power system will rely on natural gas as its principal fossil fuel source on average and at the margin. To do so effectively and reliability will require consistent regulation of the reliability of gas systems, comparable to the enforceable standards

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[48] NERC, 2022 Summer Reliability Assessment, June 2022

[49] Energy experts sound alarm about US electric grid: 'It's not designed to withstand the impacts of climate change' - CNN

and oversight NERC helps provide for electricity; availability of the gas system data needed to assess gas fuel supply risks; and gas spot markets that are co-optimized with ISO/RTO markets and real-time power system operations to enable gas generation to balance the variability of renewables and rapidly respond to power system requirements during high impact events.

- Development of resilient systems will become an even more critical part of the planning and implementation structure of the industry. Following FERC's definition of resilience as including the capability to anticipate, absorb, adapt to, and/or rapidly recover from disruptive events, there is a need for utilities to have from better resilience metrics; broad participation in resilience planning, and changes in the structure and operation of power systems that reflect greater resilience.
- Finally, there is significant need for the redesign of power markets to better compensate resources and flexible demand for reducing the probability of outages. Moving toward stochastic nodal adequacy pricing based on portfolio weather forecasts that can provide accurate and consistent compensation for the diverse resources that contribute to maintaining resource adequacy will provide a highly desirable point of departure.

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