Making Electricity Capacity Markets Resilient to Extreme Weather Events

Marie Petitet,[a] *Burçin Ünel,*[b] *and Frank A. Felder*[c]

ABSTRACT

The devastating 2021 blackout in Texas, among others, has highlighted the need to reform electricity markets to make them resilient to extreme weather events. We review related efforts by system planners and operators within electricity market contexts, focusing on Europe and the United States, and we analyze possible reforms to electricity capacity markets. To account for extreme weather events, capacity requirements and markets, along with other regulatory measures throughout the electricity and fuel supply chains, should be modified. First, capacity requirements must be tailored to the specific severe weather failure modes applicable to a given power system to achieve policymakers' reliability and resiliency objectives: reducing the frequency, magnitude and duration of blackouts. Second, all capacity requirements should be cost-effective and integrated with other non-capacity resources and requirements, such as transmission, distribution and other infrastructure systems. Third, for a capacity market to produce the desired efficiency benefits, the product (capacity) must be well-defined and backed by sufficient credit and other policies to ensure providers have sufficient incentives to perform when called.

Keywords: Electricity markets, Resilience, Extreme weather events, Natural gas infrastructure, Capacity market reforms

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ABBREVIATIONS

ACER	European Union Agency for the Cooperation of Energy Regulators
ENTSO-E	European Network of Transmission System Operators for Electricity
ERAA	European Resource Adequacy Assessment
ERCOT	Electric Reliability Council of Texas
EWE	Extreme weather event
FERC	U.S. Federal Energy Regulatory Commission
LOLE	Loss of load expectation
LOLP	Loss of load probability
NERC	North American Electric Reliability Corporation

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[a] Corresponding author. King Abdullah Petroleum Studies and Research Center. Riyadh, Saudi Arabia. E-mail: marie.petitet@kapsarc.org.

[b] Institute for Policy Integrity at NYU School of Law.

[c] King Abdullah Petroleum Studies and Research Center.

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NYISO	New York Independent System Operator
PUCT	Public Utility Commission of Texas
SARA	Seasonal Assessment of Resource Adequacy
VOLL	Value of lost load

1. INTRODUCTION

Electricity is vital for public safety, security, and health. As the 2021 events in Texas demonstrate (Busby et al. 2021), extreme weather events (EWEs) can cause devastating power outages and blackouts, resulting in fatalities, human suffering, and significant economic damage. Climate change may also increase the frequency, duration, and magnitude of EWEs (Seneviratne et al. 2012; Stott 2016), making it difficult to develop cost-effective policies to limit the effects of EWEs on power systems. Furthermore, EWEs but also variable and intermittent renewables and electrification exacerbate reliability and resiliency concerns.

Electric power systems should be designed and operated to ensure their reliability and resilience.[1] First, power systems must deliver electricity to consumers almost all of the time (i.e., reliability), although occasional outages may occur. Second, when blackouts occur, they should be limited and quickly resolved (i.e., resiliency). Most failures affecting power systems are independent and limited to one component. However, common-cause failure events (e.g., EWEs),[2] in which multiple components fail simultaneously owing to a shared cause, can occur. These multiple equipment failures over short periods reduce the ability of the power system to function and prolong its recovery from large blackouts. Furthermore, weather correlated events affect the output of solar and wind (and therefore energy storage), which also affects resource adequacy modeling and capacity markets.

Common-cause failures potentially lead to high but uncertain physical and social impacts, and there is relatively little information available regarding their frequency, magnitude, and duration compared to independent failures. EWEs also challenge power systems in the long term because system components must be able to withstand increased EWEs (with low and uncertain probabilities) and changing electricity demand.

System operators and policymakers should consider all effects of EWEs on resource adequacy. Broader criteria and metrics beyond the standard loss of load probability (LOLP) may be required to do so. First, EWEs increase the unavailability of resources and may reduce the output of generation units that remain available. For instance, during heat waves, the cooling sources for thermal power plants may be substantially warmer than during a typical summer day, thereby reducing the available capacity of these power plants.[3] Even relatively small capacity reductions across large numbers of plants will significantly impact the LOLP or other resource-adequacy metrics. Resource adequacy assessments should also capture the impact of weather on electricity generation. Correlated failures are another type of failure mode that refers to the correlated output of variable and intermittent renewables such as wind and solar.

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[1] Multiple terminologies and definitions of reliability and resiliency exist (Billinton and Allan 1984; Unel and Zevin 2018; Phillips 2019; Zappa, Junginger, and Van Den Broek 2019; Plotnek and Slay 2021).

[2] Other common-cause failures not due to weather are cybersecurity threats, operator error, maintenance practices and regulatory risks, such as the shutdown of multiple nuclear power plants due to a common safety issue.

[3] Similar effects occur in the transmission and distribution system: higher temperatures reduce the ability of power lines to transmit power, thereby limiting energy delivery to firm load.

Second, EWEs may also affect electricity demand by increasing it or shifting it among customer classes and geographic locations. Electrification that is expected to happen due to climate change policies could further exacerbate the effect of EWEs on demand. This *dependent demand* should be incorporated into the resource-adequacy models precisely because the increase occurs when less generation, transmission, and distribution capacity may be available due to severe weather.

In liberalized power systems, extreme events such as the 2021 Texas blackout have raised questions about whether electricity markets can ensure a sufficient level of reliability and resiliency, and if they can do so cost-effectively. Texas liberalized its electricity system in 2002, and since then, it has relied solely on energy (and reserve) markets, i.e., there is no capacity market, to meet reliability and resiliency expectations. Texas is considered, or at least had been considered until its recent blackout, by many economists as a role model in market design (Cramton 2017). Although capacity markets have been introduced in many regions to ensure resource adequacy, the 2021 Texas blackout questions whether introducing a capacity market in Texas could have limited the 2021 event and what features capacity markets should have in the context of EWEs.

This article investigates what capacity market reforms could be undertaken to better address EWEs and climate change. It highlights that accounting for infrequent common-cause events such as EWEs is challenging but necessary to ensure resource adequacy and resilience in the future. Section 2 reviews initiatives to address EWEs in Europe and the United States (U.S.) with an emphasis on the Electric Reliability Council of Texas (ERCOT) and identifies best practices and avenues for improvements. Once accurately included in resource adequacy studies, capacity mechanisms can partly address EWEs and other common-cause failure events. To this end, Section 3 examines potential capacity market changes to address EWEs and climate change. Finally, Section 4 concludes with policy recommendations.

2. HOW SYSTEM PLANNERS AND OPERATORS ASSESS AND RESPOND TO EWES

EWEs and climate change have been discussed in the power-related scientific literature (Klein et al. 2013; Pereira-Cardenal et al. 2014; Staid et al. 2014; Jerez et al. 2015; de Queiroz et al. 2016; Craig et al. 2018), including the 2021 Texas blackout (Busby et al. 2021; Levin et al. 2022; Shaffer, Quintero and Rhodes 2022). This section analyzes system operators' practices in Europe and the U.S.

2.1 Europe

The European Network of Transmission System Operators for Electricity (ENTSO-E) was created to coordinate the operation and planning of 39 transmission system operators (TSOs) in Europe. ENTSO-E is required to perform "a European generation adequacy outlook and an assessment of the resilience of the system" (Regulation (EC) 2009/714). Generation adequacy is a component of reliability that determines the amount of generation resources needed to meet electricity demand. In response to these tasks, ENTSO-E began developing future scenarios on a 10-year horizon, which are used in two major long-term planning studies.[4]

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[4] The two major long-term planning studies performed by ENTSO-E are the Ten-Year Network Development Plan (TYNDP) and the formerly called Mid-Term Adequacy Forecast (MAF), which has been replaced by a new study called the European Resource Adequacy Assessment (ERAA). These long-term outlooks are performed on a 10-year horizon.

Regulation (EU) 2019/943 on the internal market for electricity has reinforced the requirement to carry out resource adequacy assessments at the European level and the national level of each member state. The European Resource Adequacy Assessment (ERAA) is the cornerstone of resource adequacy assessment in Europe and is used to assess the effectiveness of in-place capacity mechanisms. Based on a European power sector model, the ERAA provides the estimated loss of load expectation (LOLE) up to ten years in the future, with and without capacity mechanisms,[5] as requested by Regulation (EU) 2019/943.

The capacity mechanisms in Europe arose from national initiatives. The European Commission has decided not to introduce a common European capacity mechanism. Instead, it considers these mechanisms as "temporary" and "last resort" solutions subject to the approval of the Commission following an inquiry (European Commission 2014; Regulation (EU) 2019/943). A necessary condition for introducing capacity markets is that both the ERAA and the national resource adequacy assessment demonstrate that the resource adequacy standards set the national level[6] are not met (Regulation (EU) 2019/943).

The following subsections identify two trends in Europe to enhance the ERAA methodology regarding EWEs and climate change on the one hand and the interlinks between power and gas sectors on the other hand. We suggest, however, that future improvements should also include common-cause events.

2.1.1 EWEs and Climate Change

As per regulations and methodologies, the ERAA must include "appropriate sensitivities on extreme weather events" (Regulation (EU) 2019/943) and climate change (ACER 2020). Therefore, ENTSO-E has progressively improved its methods (Harang, Heymann, and Stoop 2020; ENTSO-E 2021). Initially, ENTSO-E's long-term studies relied on a Monte-Carlo approach based on historical data and random sampling of forced outages.[7] As part of the ERAA improvements planned for 2023, ENTSO-E will improve its demand and generation output database to become forward-looking regarding climate change (ENTSO-E 2022).

In 2021, the first release of the ERAA (ENTSO-E 2021) included considerable improvements by integrating climate change impacts on temperatures and subsequently on electricity demand scenarios. The ERAA scenarios consider the temporal and spatial interdependency between temperatures (and the corresponding electricity demand), wind, solar PV and hydropower.[8] Future enhancements will include building climate-dependent scenarios that fully integrate climate projections.[9]

Apart from ERAA modeling improvements, ENTSO-E members also published a method to assess climate-change effects on electricity demand and hydroelectric generation using a

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[5] In the reference case without capacity mechanisms, new capacities are added in the future if their economic viability is obtained. In the case with capacity mechanisms, additional capacities are added in the European countries that have a capacity mechanism in place. As in any modeling exercise, accurately representing capacity markets remains a challenge and is subject to modeling assumptions.

[6] Europe has not defined any resource adequacy standard. Instead, each European country can define its own resource adequacy standard (metrics and values).

[7] The ERAA considers scenarios involving independent forced outages for thermal generation units and grid assets. It does not include common-cause failures.

[8] The methodology consists of analyzing the mean and variance evolution of temperatures in the historical period from 1981 to 2019, extrapolating temperatures for 2021 to 2030, and finally deriving the climate-dependent electricity demand scenarios.

[9] Integration of climate projections is developed in cooperation with Copernicus Climate Change Service. See https://climate.copernicus.eu/.

post-processing approach (Harang, Heymann, and Stoop 2020).[10] However, this method considers the increase in the mean temperature but neglects the higher frequency of EWEs, which can also significantly impact power systems, as pointed out by Chandramowli and Felder (2014).

2.1.2 Electricity and Gas Sectors

Another direction of improvement currently being undertaken in Europe is the consideration of the interdependency between the electricity and gas sectors. This directly addresses one of the causes of the 2021 Texan blackout.[11] Historically, ENTSO-E and its counterpart for the gas sector separately planned for different long-term scenarios. According to Regulation (EU) 2013/347, the first joint scenarios were released in 2016 based on a consistent, interlinked electricity-gas market and network model.

Despite this significant effort in interlinked electricity and gas modeling, the ERAA is performed by ENTSO-E based on an electricity model. Further improvements planned through 2024 will enhance the modeling to consider Power-to-X (ENTSO-E 2022), which would strengthen the interdependencies between sectors (with hydrogen or ammonia as a vector) but can also bring additional interruptible options to deal with extreme situations. Given the critical interdependence between the gas and electricity sectors, which is particularly exacerbated during EWEs, further modeling efforts should be pursued to better evaluate the complete energy system and its links. Assessments of power systems' resilience to EWEs should include common-cause failures that could affect the gas supply and thus result in a lack of electricity generation.

2.1.3 First Edition of the ERAA

Despite all its improvements, the first ERAA edition (2021) did not meet all expectations. The European Union Agency for the Cooperation of Energy Regulators (ACER) has not approved[12] the ERAA 2021 (ACER 2022). The concerns identified by ACER are not related to EWEs and climate change. However, they highlight the extent to which modeling methods are essential in resource adequacy assessment and can be debated. Despite acknowledging significant improvements made by ENSTO-E in the second edition of the ERAA released in November 2022, ACER has also decided to neither approve nor amend it because of modeling issues and the fast-changing situation in Europe (ACER 2023).

Recent improvements in ENTSO-E's methods suggest that preparing power systems for climate change has started to move to the operational phase by acknowledging its role in resource adequacy and addressing it through generation capacity mechanisms. However, the current improvements in the ENTSO-E methodology appear to be centered around the effect of increasing mean temperature due to climate change, and future improvements should consider full climate projections. To the best of our knowledge, no adjustment has been foreseen

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[10] It highlights the reverse impacts on the LOLE in the European context: (i) a decrease in electricity demand due to higher mean temperatures, which improves resource adequacy, and (ii) a decrease in hydropower generation due to lower water inflows, which worsens resource adequacy.

[11] The interdependency between the electricity and gas sectors has been pointed out as a cause of the 2021 Texan blackout (FERC-NERC 2021).

[12] ACER can either approve, request amendments or not approve the ERAA. The choice to not approve the 2021 ERAA rather than requesting amendments sent a strong message to ENTSO-E.

in the forced outage scenarios considered in the ERAA, which assumes independent outages.[13] We suggest that further improvements in the ERAA should address this gap.

2.2 United States

Recently, the U.S. Federal Energy Regulatory Commission (FERC) issued two notices of proposed rules: one is a one-time informational request from transmission operators regarding extreme weather vulnerability, climate change and reliability (FERC 2022a), and the second is the requirement for transmission system planning for extreme weather (FERC 2022b).

In these transmission system planning performance requirements, FERC directs the North American Electric Reliability Corporation (NERC) to modify its existing reliability standards. These modifications include requirements to develop benchmark planning cases based on extreme heat and cold weather events and to use analysis that covers a range of extreme weather scenarios by considering the expected resource performance during those scenarios. Over the years, NERC has analyzed multiple events that fall under the category of common-cause failures including cold weather (NERC 2014; NERC 2016). FERC recognizes that while the current standards require planners to assess their systems based on their experience, there is no requirement for analyses related to extreme weather events, especially for extreme heat and cold weather. FERC argues that if planners have the necessary data, they can identify corrective actions, such as winterizing requirements, allowing maximum transfers between regions or requiring additional reserves (FERC 2022b, paragraph 40). This can help minimize the adverse effects of EWEs and reduce system restoration time, increasing system resilience. Although these rules are focused on extreme cold and hot weather events, FERC has also asked for input on whether to include other events such as droughts, hurricanes and tornadoes.

Concurrently, FERC acknowledged a lack of information about transmission providers' current practices. Therefore, FERC also proposes requiring transmission planners to submit a one-time informational report on their current methods of assessing their systems' vulnerability to EWEs. FERC recognizes the need for more transparency on vulnerabilities' assessments.

FERC's proposals illustrate the actions being undertaken in the U.S. to better consider the effects of weather and climate change on power systems. Even before FERC's rulemaking, some operators had already begun modifying their practices. The New York Independent System Operator (NYISO) released its "Climate Change Impact and Resilience Study" in September 2020 (Hibbard et al. 2020), which was a "deterministic, scenario-based assessment of system operations" in 2040. This assessment included developing potential load and resource mix scenarios based on New York's climate targets, technology trends and other demand drivers such as temperature. It also included running EWE scenarios, such as temperature waves and storm disruptions, and calculating metrics such as loss of load occurrences. NYISO first looked at a baseline scenario that met New York's clean energy goals but without various physical disruptions to the grid. In these baseline scenarios, they analyzed the magnitude, duration and frequency of the loss of load occurrences, reliance on dispatchable emissions-free resources and price-responsive demand for balancing. They then analyzed the same metrics with disruptions to understand EWEs impact. Although NYISO's analysis and its scenarios were not

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[13] ENTSO-E identifies and analyses common-cause failures extreme events as part of the so-called Risk Preparedness in accordance with Regulation (EU) 2019/941. The types of events considered include EWEs, such as heat waves or cold spells, but also fuel shortages or cyberattacks. Risk Preparedness focuses on the short-term and has no direct relationship with capacity market implementation. We suggest that events identified in the Risk Preparedness should be considered in long-term analyses such as the ERAA.

as comprehensive as those of ENTSO-E, they still revealed insights for making the New York power system more resilient.[14]

2.3 Texas

Before February 2021, and until now, the Electric Reliability Council of Texas (ERCOT) had a reserve margin goal set at 13.75% of the peak load (ERCOT 2023). In 2012, ERCOT commissioned a loss of load study, but it did not explicitly consider EWEs or climate change (ECCO International, Inc. 2013). However, ERCOT does consider droughts, an example of EWE, as part of its deterministic resource adequacy analysis (ERCOT 2013).

Like most regions, ERCOT typically does a Seasonal Assessment of Resource Adequacy (SARA), looking ahead less than a year. The SARA report assesses whether sufficient operating reserves are available. The last SARA done before 2021 blackout concluded that "there will be sufficient installed generating capacity available to serve system-wide forecast" despite operating reserve being below the threshold in one scenario.[15]

After the 2021 blackout, ERCOT and the Public Utility Commission of Texas (PUCT) also implemented changes, including reforms to the ERCOT energy market (PUCT 2021). However, these changes were driven mainly by legislative directives based on qualitative analyses performed by outside experts (Wood III et al. 2021), and they were based on political acceptability rather than internal ERCOT resource adequacy or resilience modeling. The legislation created a committee to map the electricity supply chain and sources needed for critical infrastructure during EWEs. In September 2022, the PUCT adopted weather preparedness rules (PUCT 2022) that include a process to review critical generation and infrastructure components.

At the end of 2022, in a politically controversial move, the PUCT recommended a novel "Performance Credit Mechanism," under which dispatchable generators would earn credits if they produce during the highest-risk hours of the year (Foxhall 2023).[16] Depending on the final design, it could raise potential efficiency problems (e.g., uncertainty, market power issues, lack of efficient non-performance penalties) (Institute for Policy Integrity 2022; Bates White Economic Consulting 2023). It prioritizes resource adequacy without addressing the resilience challenges of EWEs. In addition, in March 2023, the PUCT started a process to reform its reliability metrics and invited comments on how locational, seasonal, and extreme weather considerations could be incorporated (PUCT 2023).

3. REFORMING INSTALLED CAPACITY MARKETS TO ACCOUNT FOR EWES

In many regions of the world, capacity markets are used to ensure resource adequacy. Generation capacity, however, is not always the most cost-effective solution for improving the reliability and resiliency of power systems. Instead, investing in other elements of the electricity supply chain may be more cost-effective (Felder and Petitet 2022). In the context of EWEs,

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[14] For example, it was revealed that the system was more vulnerable to storm disruptions than to temperature waves or wind lulls.

[15] While the report did not provide an explicit discussion of this scenario, the overall conclusion is likely based on ERCOT's belief that these values represent a lower bound and that the actual reserves available would be higher due to the market price signals (or that the probability of the scenario occurring is low).

[16] These high-risk hours would be determined after the end of the compliance year, and the load-serving entities would have to procure credits based on their share of consumption during these hours.

this section focuses on capacity markets as they are currently being used to address resource adequacy. This section also discusses broader challenges related to the entire electricity supply chain. Finally, we propose six directions to enhance the market design to account for EWEs and use them to provide tailored recommendations for Texas.

The characteristics and efficiency of capacity markets are widely discussed[17] with high renewable penetration (Bhagwat et al. 2017; Byers, Levin, and Botterud 2018; Kraan et al. 2019; Botterud and Auer 2020) and new sources of flexibility (Khan et al. 2018; Lynch et al. 2019; Fang et al. 2021). Capacity markets are also analyzed regarding their interaction with other markets or mechanisms (Bialek, Gundlach, and Pries 2021; Bialek and Ünel 2022), and solutions to integrate them with renewable support schemes have been proposed (Spees et al. 2021). To the best of our knowledge, the capacity market's ability to deal with EWEs and climate change still needs to be addressed, which this section does.

3.1 Structure of Capacity Markets

The starting point for capacity markets is a resource adequacy requirement. In practice, different metrics are used to determine the level of resource adequacy. However, common ones are LOLE and LOLP used to calculate the aggregate level of capacity that a wholesale market requires (ENTSO-E 2021).[18]

Although many features vary across capacity markets,[19] their critical components are capacity requirements based on a resource adequacy analysis that is imposed on load-serving entities or a central authority. They should be able to fulfill the allocated requirement through the self-provision of capacity, by purchasing capacity from other entities or by reducing their load, and therefore, their capacity obligation. In short, capacity markets are a floor-and-trade mechanism that internalizes the positive reliability externality provided by capacity (Jaffe and Felder 1996). Alternative capacity mechanisms (De Vries 2007; Batlle and Rodilla 2010) include strategic reserves, i.e., the reservation of some generating capacity in return for an annual fixed payment, to provide an additional reserve in case of extreme need. These mechanisms also include capacity payments, i.e., annual fixed payments to certain or all generating units to acknowledge their physical capacity.

Capacity markets are consistent with transferring resource adequacy responsibility to capacity owners instead of consumers. They also introduce a capacity market price risk to capacity owners, which incentivizes them to perform. However, the physical risk still affects consumers as they face potential blackouts. In some designs, bilateral contracts allow the load to decide its level of risk, while system operators achieve the desired resource adequacy level (Oren, 2003). Some of the U.S. Regional Transmission Organizations have and continue to incorporate EWEs into their capacity markets.[20]

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[17] There is a long literature critiquing capacity markets. See Aagaard and Kleitt 2022 for a review. Mays, Morton and O'Neill 2019 discuss air emission implications.

[18] In practice, different definitions of these metrics are implemented. Another resource-adequacy metric is Expected Unserved Energy (EUE), which accounts for the magnitude of the blackout.

[19] A non-exhaustive list includes capacity deliverability requirements that account for transmission constraints, quantifying the capacity value of different generation resources, particularly hydroelectric and intermittent renewables; penalties, if any, for non-performance; derating capacity for unavailability; forward capacity requirements; whether demand response counts as capacity; subregional capacity markets; administrative demand curves and so on.

[20] For example, in February 2023 PJM has fast tracked ongoing capacity market reforms motivated in part by substantial generation outages during a winter storm in December 2022 (Howland 2023). In 2014, PJM also amended its capacity market rules due to the January 2014 polar vortex (POWER 2014).

3.2 Going Beyond the Pitfalls of Current Capacity Markets to Consider EWEs

If capacity markets are to be modified to account for EWEs or other common-cause events, we identify six challenges to be addressed.

3.2.1 Overcoming Data and Modeling Challenges

Underlying resource-adequacy models that determine the aggregate amount of capacity needed for an electricity market do not generally reflect the threats that EWEs or other common-cause failures can bring, as illustrated in the European and U.S. contexts. EWEs violate the assumption that all generation failures are independent. Moreover, even relatively low-probability EWEs can have a major impact on the reliability and resiliency of power systems because of the extent of the damage they can cause. This can result in the simultaneous widespread and long-duration unavailability of generation units, as demonstrated by the 2021 Texas blackout.

There are numerous challenges in incorporating EWEs into resource-adequacy modeling. First, the data on EWEs are limited, resulting in wide uncertainty ranges. Second, data on the impact of EWEs on the power sector are also limited. The same or similar EWEs may have very different implications for power generation, transmission and distribution, further complicating the uncertainty analysis. Third, owing to climate change, the frequency, duration and magnitude of extreme weather may be non-stationary, further increasing the uncertainty of each of these elements. After incorporating these data uncertainties in standard resource adequacy simulations, the statistical distribution of critical metrics can be estimated, and then be used to incorporate risk aversion into the analysis (Felder, 2001).

Fourth, the value of lost load (VOLL), or the analog of social welfare of consuming one more unit of electricity, may differ in small-scale events where the load is disconnected versus large-scale blackouts. Losing electricity for several hours for a small percentage of the load does not raise the same level of public security and health consequences, and associated equity issues, that would be raised if more significant numbers of the population lost electricity for extended periods.[21] These VOLL discrepancies should be considered in resource adequacy assessments (Felder and Petitet 2022; Gorman 2022). Fifth, the modeling exercises should not be limited to the power sector. They should consider the entire value chain because fuel supply systems now potentially affect the available capacity. Thus, it may be necessary to extend resource adequacy analysis to include natural gas pipelines (as New England is considering, see Kaslow (2019) and ISO-New England (2018)), railroad transport, communication systems and other supporting infrastructure.

Gathering EWE data and developing resource-adequacy models that address these characteristics and are acceptable for the public policy process will take time. The first steps in this direction can already be observed[22], but further efforts should be undertaken. Transparency and easy-to-access data and models would also be an accelerating factor in this journey.[23]

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[21] Many facilities needed for public health that do not have backup power supplies, such as pharmacies, dialysis clinics, and long-term care facilities, would be inoperable or restricted in their operations due to an extended blackout.

[22] See for example initiatives from research organizations such as EPRI (2022) and Murphy, Lavin and Apt (2020), or improvements by system operators, as discussed in Section 2.

[23] In the European context, data are available on the ENTSO-E website, and the Antares Simulator (https://antares-simulator.org) is an example of an open-source model that is used by ENTSO-E for resource adequacy assessments. In the U.S. context, GridLab carries out an open-source initiative for advancing resource adequacy analysis with available data and tools (Hart and Mileva 2022).

3.2.2 Setting the Optimal Level of Resource Adequacy Commensurate with Transmission and Distribution Systems

The various metrics used to inform resource adequacy are debated (Ibanez and Milligan 2014; NERC 2018), and selecting one always provides a one-sided view of the adequacy's complete picture. Where capacity mechanisms are in place, the LOLP or its equivalent threshold is typically not set at a level that maximizes social welfare; instead, it is based on engineering judgments and historical practices. Several studies in the U.S. context set the LOLP to be much lower than is warranted, given the VOLL (Carden and Wintermantel 2013; Pfeifenberger et al. 2013).[24] Instead, the marginal benefits of avoiding a blackout should be equal to the marginal costs of doing so (Felder and Petitet 2022) for a risk-neutral decision-maker with quantifiable uncertainties. As this historically based LOLP requirement is applied to resource-adequacy models that do not incorporate common-cause failures such as EWEs, the requirement results in the building of excess generation that is unavailable during EWEs.

EWEs are infrequent in nature, but their frequency, duration and magnitude may increase in the future (Seneviratne et al. 2012; Stott 2016). This further complicates defining the appropriate level of resource adequacy. The social costs of blackouts due to EWEs are challenging to estimate, as illustrated during the 2021 Texan blackout (e.g., different cost estimations are provided in Golding, Kumar and Mertens (2021)).

Given current practices, capacity requirements are generally defined while implicitly assuming that transmission and distribution systems are sufficiently reliable to deliver the available capacity when converted to energy to firm load. In practice, the effectiveness and efficiency of the capacity market explicitly depend on these other systems. An efficient solution to reach a given level of resource adequacy involves the right combination of generation capacities, transmission and distribution, and other elements of the electricity supply chain. Moreover, the reliability and resiliency of the entire system should be equivalent to the social optimum.[25]

Consequently, setting the optimal level of resource adequacy and resiliency commensurate with the transmission and distribution systems, and at the socially optimal level, requires addressing modeling challenges similar to those in the generation sector. In setting this level, it is important to use limited resources, given the need to achieve reliability and resiliency levels for the power sector in a cost-effective manner. This is also important for freeing up resources to address air pollution and climate change, among society's many other pressing priorities. Furthermore, owing to the non-stationarity of EWEs, this issue needs further analysis.

3.2.3 Ensuring Accurate Availability of Generation Units and Other Critical Elements Through a Combination of Market and Regulatory Requirements

Once the level of resource adequacy is determined, achieving that level through a capacity market is challenging. The "capacity" product is often complex to define and even tricky for certain technologies such as storage and variable renewables (Zachary, Wilson, and Dent 2022). Recent focus has been on improving resource adequacy modeling, including applying and improving the calculation of effective load-carrying capability of various resources

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[24] In the transition to electricity markets, concerns were raised that markets would reduce reliability. It is, therefore, not surprising that policymakers used the historical engineering resource adequacy requirements, even if these requirements resulted in overinvestment in capacity, to avoid the criticism that electricity markets would reduce reliability.

[25] This is the analog of the *equimarginal* principle from environmental economics. In power systems, applying this principle results in the *coordination equation*.

given increased levels of wind, solar and energy storage and their definition of capacity credits (Bothwell and Hobbs 2017; Söder et al. 2020; Energy Systems Integration Group 2021). Moreover, the final objective of such mechanisms is to allow for a reliable and resilient power system, whereas "capacity" is a means but not a goal. Capacity must be converted into energy and delivered to the load, and this conversion does not always occur because of transmission and distribution limitations, generation unit failures, and resources' availability. Defining and measuring a product becomes even more important given the different generation profiles of renewable resources. Understanding the contributions of all resources, including renewables, fossil fuels and demand response, to reliability under EWEs is critical for ensuring the continuity of the power supply.

Numerous options exist to enhance availability of generation units or other critical elements. We consider three options: fuel diversity requirements, substantial penalties for non-performance, and severe weather standards. Their selection depends on the combination of the ability to define a verifiable and measurable product, the administrative burden imposed by a particular design choice, the implications for market power and the ability of entities that provide such capacity to recover their costs in a socially efficient way. An example illustrates the interdependencies among these factors. Consider a proposal in which the capacity must have two fuel sources to qualify.[26] Such a requirement excludes nuclear, hydroelectric, wind and solar generators unless energy storage counts. Thus, either these technologies would have to be exempted or some other type of requirement would need to be imposed to ensure that the capacity is available during EWEs. Furthermore, such a requirement would not result in a natural-gas-fired unit investing in the weatherization of its natural gas infrastructure, which may be more cost-effective and reliable than having a backup fuel source such as oil.[27]

Instead of having a fuel diversity requirement, the capacity market could impose substantial penalties if the capacity does not deliver during EWEs, perhaps imitating the incentives of the energy spot market. Penalty setting should induce efficient investments in making capacity reliable and resilient. At the same time, the penalty should not penalize resources for non-performance during periods when they cannot be reasonably expected to perform.[28] Moreover, credit policies must be commensurate with penalties to ensure collection. Otherwise, the capacity provider could declare bankruptcy to avoid payment.

Another approach would be to require that the capacity resource be able to meet a severe weather standard, such as being available during a one-in-fifty-year cold snap or delivering when temperatures are below a certain level or above another level. In both cases, verifying the capacity ability would have to be done without the conditions, which require intrusive testing

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[26] When not all capacities are allowed to participate in a capacity market (e.g., because of fuel requirements), it is also necessary to develop a proxy to consider the contribution of these out-of-the-market capacities to resource adequacy. This situation may be challenging and complex to implement. Methods to estimate the contribution of "out-of-capacity-market" technologies to resource adequacy can further introduce a discrepancy between implementation and resource-adequacy models if not updated with implementation rules. This potential discrepancy is similar to the discussions in the U.S. regarding expanding the use of a minimum offer price rule to subsidized clean energy resources, which made it more difficult for these resources to clear the capacity market and hence ignored their resource adequacy contributions. Those rules are either fully rescinded or being phased out currently (Aagaard, Palmer and Robertson 2022).

[27] Similarly, PJM had a rule that required batteries to have the capability to discharge for a 10-hour duration to participate in its capacity market. While it was in effect, this requirement prevented shorter-duration batteries from participating in markets, even when they could have provided capacity value during shorter periods of capacity needs.

[28] For example, if an EWE leads to a blackout during the night, a solar resource should not be penalized for not generating during the night.

and verification. Setting the fifty-year requirement is difficult because of the non-stationarity of the weather.

In summary, the appropriate public policy response to EWEs based upon a cost-benefit analysis is tailoring a combination of market mechanisms and regulations to a particular context. For a given power system, a cost-effective approach could vary by type of EWE and contain a combination of capacity market reforms, regulatory mandates, incentive regulation, and competitive procurement. Selecting among these and other options depends on the existence of market power, transaction costs, innovation, and uncertainty on critical parameters, such as the probability of EWEs.[29]

3.2.4 Ensuring Sufficient Revenues

A well-functioning power system should allow revenues that cover the costs of all capacities required to reach a sufficient level of resource adequacy. Cost recovery has become an issue when reforming capacity markets to account for EWEs. Currently, U.S. capacity markets use a levelized cost of marginal capacity to set a cap on capacity prices and to structure a capacity demand curve (Bowring 2013; Spees, Newell, and Pfeifenberger 2013). Determining this levelized cost is nontrivial and becomes even more complicated if fuel availability and weatherization costs are considered. Is the marginal cost of capacity the cost of a combustion turbine or a combustion turbine with fuel weatherization, energy storage or something else? Whether the cost-based demand curve is the right approach or whether it should be revised to a reliability and resiliency value-based approach is a question worth considering.

Another question is whether capacity-related weatherization costs are recovered via capacity markets or whether they can be recovered via transmission or distribution tariffs as regulated costs. The latter can be done, for example, through blackstart costs in the U.S., but it raises regulatory difficulties. Furthermore, a capacity resource may be needed for EWEs but is otherwise uneconomic, increasing the need to have an analog of reliability-must-run contracts (Wolak and Bushnell 1999).

3.2.5 Incentivizing Flexibility in the Capacity Market through Demand Response

Flexibility is a topic widely discussed in short-term electricity markets. Some capacity markets consider load to be inflexible, and they provide incentives to build generation capacities to meet resource adequacy, regardless of the load. Exceptions include PJM and France, where demand response can directly participate in the capacity market in the same way as generation capacities, owing to a method that estimates its contribution to reducing the load capacity requirement.

Without load management, electrification and new technologies would require more installed capacity. However, their load is flexible and should be incentivized by capacity markets or other mechanisms to help reduce future capacity requirements. New technologies, including smart meters, can be used to improve flexibility in capacity markets. For example, it can help to select and disconnect loads, thus allowing resource adequacy to be defined at the grid mesh level.

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[29] The authors thank one of the anonymous reviewers for this paragraph.

3.2.6 Limiting the Exercise of Market Power

Since their introduction, and similar to other markets, concerns have been raised regarding the exercise of market power in capacity mechanisms. For example, having a forward capacity market in addition to a short-term market is a solution to allow new capacity entries to compete with the existing capacity to reduce market power.

More frequent EWEs may exacerbate the potential exercise of market power unless the contractual obligations of providing resource adequacy have sufficient monitoring and penalties to avoid capacity's withholding. During these events, almost all capacity providers have market power and therefore have an incentive to withhold capacity, which affects the amount of available capacity in the market, to increase wholesale electricity energy prices profitably.

3.3 Tailored Recommendations for Texas

Back in 2021, Texas did not have a capacity market in place. Other regions of the U.S. that have capacity markets (e.g., PJM and New England) have experienced problems with resource adequacy during EWEs. Thus, a capacity market in Texas would likely not have been sufficient to avoid 2021 blackout, but it might have reduced its impact if it were designed to take EWEs into account, as described below.

Designing and implementing such a capacity market takes time. And it is important to first address the root causes of the 2021 blackout with directed regulatory solutions while other solutions could be developed. FERC-NERC (2021) identified the lack of fuel supplies' weatherization, the low level of interconnection with its neighbors, and load shedding operations as the main causes of the blackout.

First, Texas should impose legal or regulatory requirements to weatherize electricity generation and fuel supplies, such as the Texas Grid Weatherization Law (Office of the Texas Governor 2021). While doing so, a particular focus should be on developing immediate solutions to allow Texas to prepare for the upcoming winter. Second, Texas should consider ways to increase transmission transfer capabilities between ERCOT and its neighbors, even if limited to EWEs, although we recognize that this might have implications about expanding federal oversight of ERCOT. To ensure cost-efficiency at the system level, a detailed adequacy analysis should be carried out to identify the adequate level of interconnections with each neighbor.

In the longer term, if a capacity market were to be implemented in Texas, we recommend addressing the six focus areas identified in Section 3.2 and tailoring them to Texas's specific context. Texas is developing reforms, but not the necessary risk and cost-benefit analyses. Reforms under discussion and already acted touch upon various elements of the electricity value chain. These actions may be the right combination of instruments, even though the details of the implementation would determine their success. However, Texas should also develop the capabilities to conduct probabilistic risk assessments to inform cost-benefit analysis and regulatory-market solutions. The methodology of such a study should explicitly include EWEs and climate change as discussed in Section 3.2. These methodological improvements can be progressively implemented based on global best practices (e.g., best practices from power systems' players like ENTSO-E and research organizations like EPRI (2022) and Murphy, Lavin and Apt (2020)).

First, resource adequacy assessments should be enhanced to include relevant cold and heat events that may happen in Texas, and to include climate change. Given that Texas has already a substantial share of its electricity from renewables, it is also necessary to develop extensive renewable datasets. Second, cost-benefit analysis should be conducted to determine if weatherization and other measures being proposed are cost effective to ensure the desired level of resource adequacy. The analysis should assess and compare all the proposed measures (e.g., the performance credit mechanism, the dispatchable energy credits, the lowered energy price cap) and other potential measures. It should also specifically address whether generators' revenues are sufficient and whether market power could arise in the context of these reforms. Third, load flexibility should also be incentivized.

4. CONCLUSIONS

The 2021 blackout in Texas and other events worldwide have highlighted the new challenges of EWEs and climate change on power systems resource adequacy. Power systems and markets must be resilient to EWEs, reducing the frequency, magnitude, and duration of potential blackouts. Modeling techniques, policies and markets mechanisms should be enhanced to address reliability and resiliency of power systems in the context of EWEs and climate change.

European and U.S. regulators have acknowledged the importance of EWEs and climate change, but further improvements are necessary to better consider them in reliability and resiliency analyses. In Europe, resource adequacy does consider climate change's impacts on electricity demand and electricity generation, but EWEs are not explicitly assessed. In the U.S., policies addressing EWEs are being considered, but they do not specifically focus on capacity markets.

When capacity markets are implemented, we propose three criteria for evaluating whether and how to use capacity requirements and associated markets to address EWEs. These criteria would require to be complemented by additional features tailored to the specificities of each region.

First, capacity requirements must achieve policymakers' reliability and resiliency objectives. This should be done by fitting them to the specific severe weather failure modes applicable to a given power system. Achieving these objectives requires basing capacity requirements on enhanced resource-adequacy models that include EWEs and other common-cause failures.

Second, any capacity requirement should be cost-effective and integrated with other non-capacity requirements, such as those for transmission, distribution, fuel supply and other infrastructure systems. Considering the entire power supply chain and its interrelationships with other critical infrastructures is necessary to ensure resiliency. To the extent that VOLL is used to inform resource-adequacy policies, it should account for the public safety and health aspects of EWEs, including their inequities.

Third, a well-defined and measurable capacity product must be developed for a capacity market. The methodology must address infrequent EWEs. Moreover, sufficient credit and other policies must be established to incentivize capacities to perform. This performance attribute should be tailored to every region based on the relevant EWEs or other vulnerabilities that may arise there.

Reforming capacity markets to account for EWEs and other common-cause events is challenging. It requires updating resource adequacy modeling to incorporate common-cause capacity and demand dependencies and adjusting the definition of capacity. It also requires trading off between regulatory and market-based mechanisms to ensure capacity performs as desired and having a cost recovery mechanism that induces the desired resource adequacy investment cost effectively.

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