مركز الملك عبدالله للدراسات والبحوث البترولية
King Abdullah Petroleum Studies and Research Center

One Year After the Texas Blackout: Lessons for Reliable and Resilient Power Systems

Marie Petitet, Khalid AlHadhrami and Frank A. Felder

April 2022

Doi: 10.30573/KS--2022-DP09

About KAPSARC

The King Abdullah Petroleum Studies and Research Center (KAPSARC) is a non-profit global institution dedicated to independent research into energy economics, policy, technology and the environment across all types of energy. KAPSARC's mandate is to advance the understanding of energy challenges and opportunities facing the world today and tomorrow, through unbiased, independent, and high-caliber research for the benefit of society. KAPSARC is located in Riyadh, Saudi Arabia.

This publication is also available in Arabic.

Legal Notice

Abstract

In February 2021, Texas experienced an extreme cold snap causing a dramatic electricity blackout that left millions of households without electricity, resulting in over 200 fatalities and economic damages of approximately $100 billion. The Texas blackout has been used to support a variety of claims regarding renewable energy, electricity markets and climate change. We identify the blackout's drivers and what has been learned since then. These lessons apply to power systems worldwide, including those of the Gulf Cooperation Council and the broader Middle East and North Africa region.

1. **Introduction:** The 2021 Texas Blackout

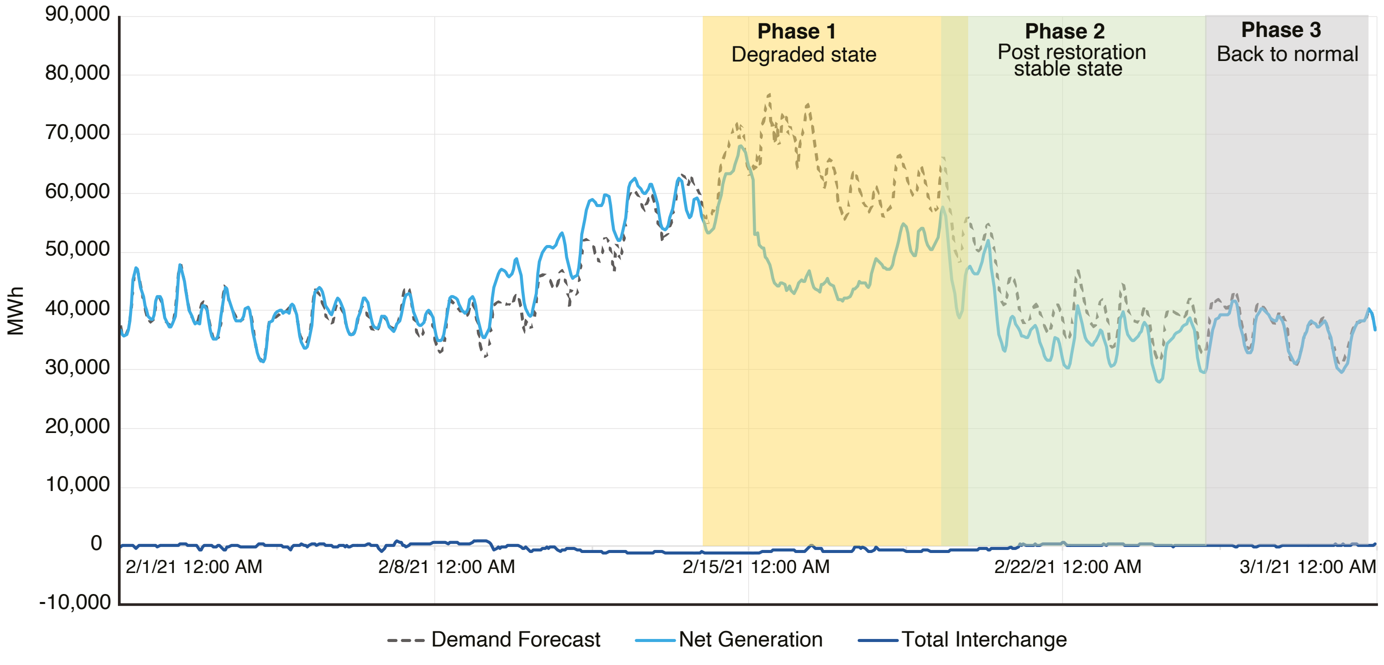
On February 15-18, 2021, Texas experienced severe winter storms that led to significant and long-lasting power outages, with firm load shedding of an average of 14 GW for almost 70 hours (FERC-NERC 2021). This resulted in more than 4.5 million households being left without electricity (FERC-NERC 2021), some for as long as four days, and at least 210 fatalities (Hauser and Sandoval 2021). The two main contributing factors to the blackout were high electricity demand to meet heating needs (demand that was underestimated by 14%) and extensive and unexpected failures of generation caused by the severe winter storm (FERC-NERC 2021).

As shown in Figure 1, the first phase of the event was characterized by a significant discrepancy between actual generation and forecasted demand (see phase 1). Then, the system stabilized but was still unable to meet the forecasted demand (see phase 2). Finally, the system returned to normal, and demand was met (see phase 3).

The economic damage has been estimated by the Dallas Federal Reserve Bank at $80 billion to $130 billion of direct and indirect costs, $4.3 billion in total value of loss load[1] and $10 billion to $20 billion in insurance costs (Golding, Kumar and Mertens 2021). Wholesale gas and electricity prices soared: natural gas prices increased by a factor of 40, and electricity prices reached $9,000 per megawatt-hour (the price cap of the ERCOT[2] market), an increase by a factor of 200.

This extremely cold weather event was not the first one experienced in Texas. Four other events that impacted the South Central U.S. and Texas have occurred over the past 40 years: December 1983,

Figure 1. Overview of forecast demand, net generation and total interchange (in MWh) in Electric Reliability Council of Texas (ERCOT) in February 2021, Central Time.



Source: Authors, based on data from the EIA (2021a).

December 1989, February 2011, and January 2018. Understanding the impacts of these weather events is necessary for the development of cold weather preparedness plans and protection measures for the electric grid and natural gas infrastructure facilities. Table 1 compares these five events. The table shows that the 2021 event was the most extreme in terms of low temperatures and wind speeds compared to the events of 2011 and 2018. However, the Texan bulk power system faced similar problems during these events, namely freezing and gas fuel supply issues, for which data collection and analysis could have helped to better prepare the system for such extreme weather events.

Historically, Texas experiences its electricity peak load in the summer, when temperatures are high and air conditioning is necessary. Its highest peak load was 74.8 GW in August 2019, which was surpassed during the February 2021 blackout, which had a peak load estimated at 76.8 GW (FERC-NERC 2021). However, since this peak load was reached during an extreme cold event, the electricity supply chain failed to deliver enough electricity. Texas has not experienced a significant blackout related to heat waves, but major concerns were raised for the summer of 2021 regarding “elevated risk of energy emergencies” (NERC 2021a).

Table 1. Overview of major winter events in Texas.

Cold weather event	Unavailable generation due to cold weather, at worst point (MW)	Causes of unavailable generation	Temperature (°C)	Peak wind gusts (km/h)	Noteworthy observations
1983 (December 20-26)				55	7 separate cold fronts during this event
1989 (December 19-25)				55	Coldest recorded winter for the Galveston/ Houston area.
2011 (February 1-6)	14,702	Freezing Issues, Mechanical/ Electrical Issues, Natural Gas Fuel Issues	9 to 20 below average	50	Blackout occurred with a maximum load shed of 5.4 GW.
2018 (January 12-18)	15,600	Freezing Issues, Mechanical/ Electrical Issues, Natural Gas Fuel Issues	7 to 16 below average	51	This event was most severe east of Texas. Only voluntary load management occurred.
2021 (February 12-20)	65,622	Freezing Issues, Natural Gas Supply Issues, Mechanical/ Electrical Issues	22 to 28 below average	66	Most similar to 1983 event: long period of cold with multiple fronts affecting a wide swathe of the U.S.

Source: Authors, based on FERC-NERC (2021).

1. Introduction: The 2021 Texas Blackout

During the February 2021 Texas blackout, renewables were identified by some as a cause of the power system failure, for example some media outlets and Texas Governor Greg Abbott on February 14-15, 2021 (Carlson 2021; Reuters Staff 2021). Later, multiple reports (FERC-NERC 2021: Energy Institute of the University of Texas at Austin 2021) found that all generation technologies experienced significant failures due to extreme weather conditions and that renewables were not the major problem given that the share of renewable generation is usually low during this period of the year.

Given the severity of the February 2021 Texas blackouts and the debates it initiated regarding the roles of wind and solar, market structure and political and regulatory failures, several lessons can be learned. This paper discusses the key lessons it holds for other power systems, including those not susceptible to extremely cold weather. The remainder of this paper proceeds as follows. Section 2 provides preliminary background. Section 3 proposes six key lessons for reliable and resilient power systems that apply to power systems worldwide, including those of the Gulf Cooperation Council (GCC) and the broader Middle East and North Africa (MENA) region. Finally, section 4 concludes with recommendations for policy makers.

2. Background on Reliability, Resiliency and Renewables

The 2021 Texas blackout highlighted the importance of reliable and resilient power systems, particularly during extreme events. Before discussing the lessons from this blackout and other major ones, this section briefly presents the necessary background regarding reliability and resiliency analytical frameworks for power systems. It also discusses the development of renewables and their related consequences for power systems.

2.1 Importance of Defining Reliability, Resiliency and other Related Terms

Ideally, power systems are designed to meet the electricity demand almost all the time. There are multiple and competing definitions of reliability and resiliency in the context of electric power systems (Billinton and Allan 1984; Kahnamouei, Bolandi, and Haghifam 2017; Phillips 2019; Zappa, Junginger, and van den Broek 2019; Plotnek and Slay 2021). Table 2 presents definitions of some terms from operational handbooks in the U.S. and Europe. Resiliency is generally not defined in these handbooks, but instead reliability is used. In the academic literature, the definition of resiliency has changed substantially over time (Plotnek and Slay 2021).

To avoid overlap with the definition of reliability, resiliency can be defined as what happens after a disruptive event (Phillips 2019); that is, the ability of the grid to recover from an uncontrolled or cascading

Table 2. Definition of key reliability-resiliency terms.

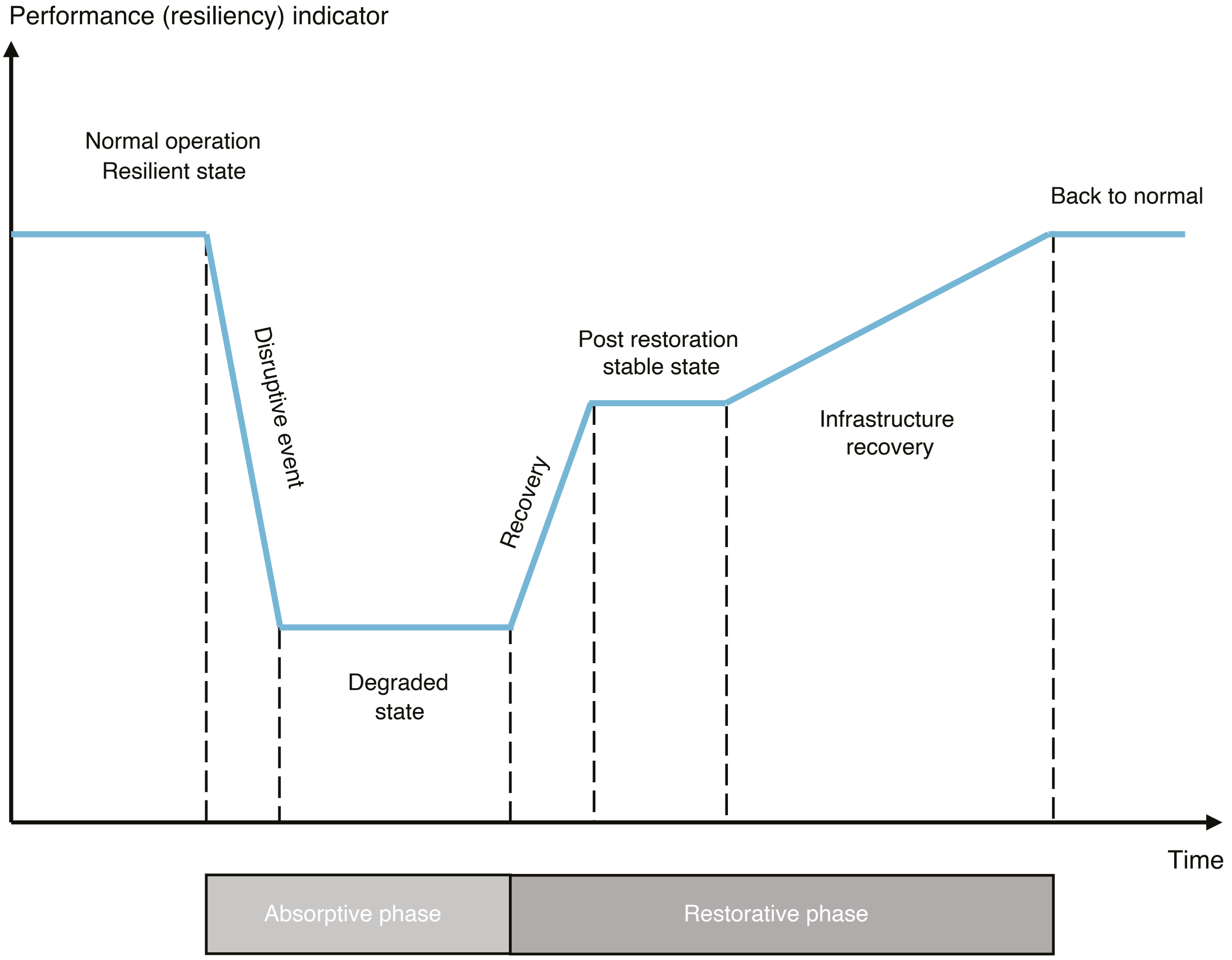
	U.S. definition	European definition
Adequacy	The ability of the electric system to supply the aggregate electrical demand and energy requirements of the customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements. (NERC 2021b; UCTE 2004b)	
Reliability	A measure of the ability of the system to continue operation while some lines or generators are out of service. Reliability deals with the performance of the system under stress. (EIA 2022) Operating reliability is the ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system components. (NERC 2007)	The degree of performance of the elements of the bulk electric system that results in electricity being delivered to customers within accepted standards and in the amount desired. It can be measured by the frequency, duration and magnitude (or the probability) of the adverse effects on the electric supply/transport/generation. Electric system reliability can be addressed by considering two basic and functional aspects of the electric system, which are adequacy and security. (UCTE 2004b)
Security	Used until 2001 in place of operating reliability. After 2001, security is not defined in the NERC handbook and seems to be used in practice to refer to critical infrastructure protection.	The ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements. (UCTE 2004b)
Stability	The ability of an electric system to maintain a state of equilibrium during normal and abnormal system conditions or disturbances. (NERC 2021b; UCTE 2004b)	

N.B.: NERC stands for North American Electric Reliability Corporation.
Sources: Authors, based on NERC (2007), NERC (2021b) and EIA 2022 for U.S. definitions and UCTE (2004b) for European definitions.

blackout or rolling blackouts. The level of resiliency depends on resiliency policies that are, of course, undertaken prior to outages. Resiliency also embeds the ability to recover from extreme events that are characterized by high impacts and low probabilities (EPRI 2022).

No matter how terms are defined in reliability handbooks, the objective remains to ensure that a power system can recover to a normal resilient state after a disruptive event happens, as illustrated in Figure 2. The normal operational state corresponds to a resilient situation that can be described as robust and resistant (Panteli and Mancarella 2015). After a disruptive/critical event, the power system is stabilized in a degraded state for a certain period: an absorptive phase during which resilience is low. The restorative phase can be decomposed into two subphases: a quick operation recovery that allows the system to stabilize at a higher resiliency level, and a longer phase necessary for infrastructure (e.g., fuel supply systems, generation units, transmission and distribution networks) to recover.

Figure 2. Critical event and associated terms.



Source: Authors, based on Panteli and Mancarella (2015) and Umunnakwe et al. (2021).

To achieve reliable and resilient power systems, medium- and long-term reliability-resiliency analyses, plans and operational policies are being developed by grid operators and others to limit the frequency and time-duration of critical events. Their analyses generally follow the objectives and horizons described in Table 3.

Table 3. Typical reliability-resiliency analyses of power systems.

	Horizon	Description of analysis
Resource adequacy	Long-term	Balance between demand and supply, based on multiple scenarios of forecasted electricity demand and generation capacities. Some studies may neglect network constraints.
Transmission and distribution infrastructure planning	Long-term	Need for network developments at different spatial scales (interconnection, regional transmission or sub-regional distribution) to meet reliability standards.
Operational reliability	Mid-term	Balance between demand and supply in the mid-term, focused on extreme points, with detailed modeling of instantaneous balancing and flexibility needs.
Operational grid stability	Mid-term to short-term	Grid stability in the mid-term, focussed on a restricted number of hours in the year, with detailed network constraints and preventive and curatives actions.

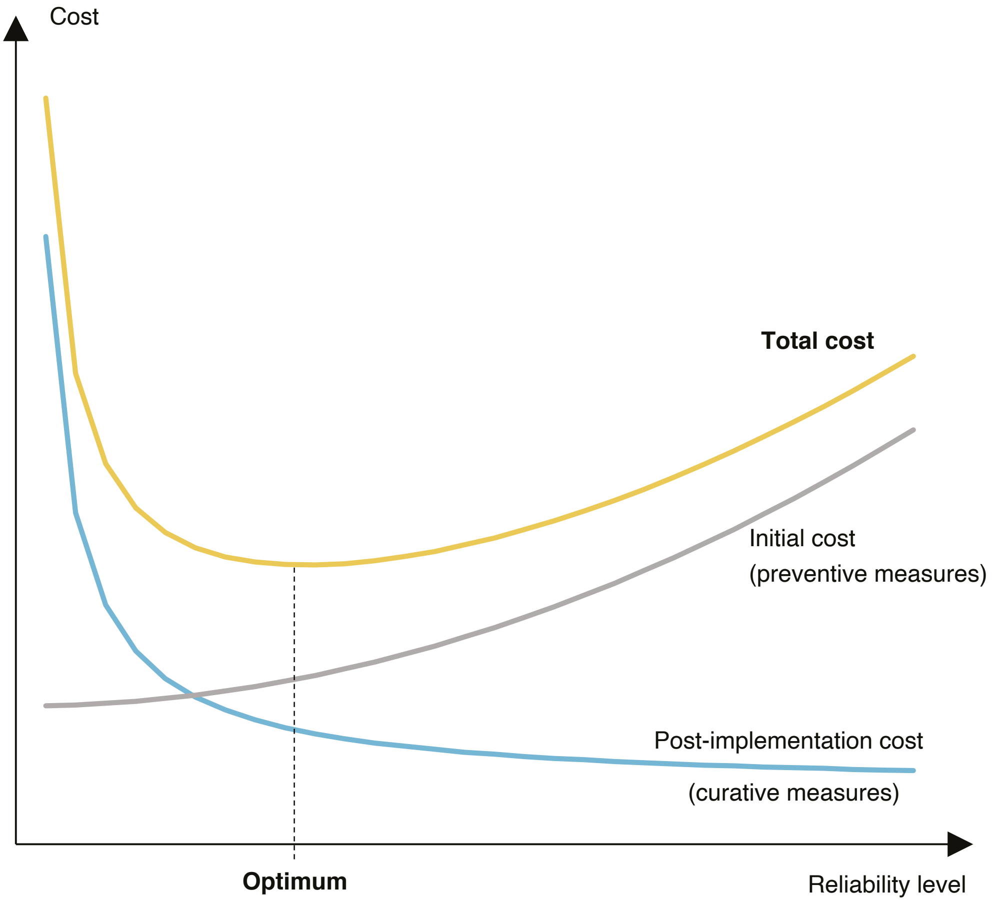
Sources: Authors, based on EPRI (2022).

2.2 Engineering and Economic Framework for Power System Reliability

Reliability standards typically have a maximum number of outage events (frequency, duration, magnitude) that are deemed socially acceptable. Historically, expected peak load (expressed in MW) was what mattered the most in plans for power system reliability. However, it is too expensive to design a power system that is always available to supply the peak load because it would require massive amounts of spare generation capacity. In response, engineering and economic frameworks were developed to describe the tradeoff between the cost of reliability and cost of unreliability. This tradeoff is based on a comparison of the additional cost to serve electricity demand and the social benefit related to consuming electricity.

The reliability and resiliency of power systems depend on actions and investments that are done before a critical event (including preventive measures) and potential actions performed afterward to mitigate the effects (including corrective measures). The tradeoff between the cost of these two elements, illustrated in Figure 3, defines the optimal reliability level.

Figure 3. Tradeoff between initial cost and post-implementation cost to define the optimal reliability level (illustrative).



Source: Authors.

To define such an optimal reliability level, data and assumptions are required, including the costs and estimated electricity demand, the probability of critical events (including common-cause ones) and their duration, and the social benefit of consuming electricity. In addition, critical weather events may change in duration, frequency and magnitude because of climate change (Seneviratne et al. 2012; Stott 2016). To avoid large blackouts, the standard engineering and economic framework should continue to be enhanced by improving methodologies and datasets. The framework should also be informed by prior blackouts, such as the one in Texas, and the occurrence of initiating events, such as severe weather (see Table 1).

2.3 Challenges Related to Large Amounts of Variable Renewable Energy in Power Systems

In the context of the energy transition, power systems are evolving to include more renewables. In 2020, approximately 115 GW of solar photovoltaics (PV) and 90 GW of wind power were added worldwide, accounting for nearly 83% of the total new generation for the year (REN21 2021). Solar PV and wind power are expected to play a key role in electricity generation in the MENA region due to their high potential and low costs. Table 4 presents renewable electricity targets in selected MENA countries. Saudi Arabia has also announced a new smart city, Neom (in the Tabuk province), whose electricity will be 100% renewable (Saudi Vision 2030 2022).

Renewables introduce technical challenges in balancing supply and demand because, for the dominate ones[4], electricity generation is non-dispatchable, variable and intermittent. There are multiple non-mutually exclusive solutions to address non-dispatchability, such as geographic diversity, improved forecasting, energy storage including electric vehicles, curtailment and active control, electrical load control, transmission enhancements, synchronous condensers, enhancing joint interconnections and operations with neighboring power systems, districting heating and cooling, heat pumps, smart meters, information and communication technology, and improved market designs, among many others. Thus, even if power systems can handle large amounts of variable renewables, it is nonetheless necessary to evaluate their reliability and resiliency along with the solutions used to address non-dispatchability. This is needed to prepare for potential reliability-threatening events that are characterized by low generation from renewables.

Table 4. Renewable electricity targets in selected MENA countries, by share of electricity produced by renewables relative to total electricity generation.

	2023	2030	2050
Algeria		37% [a]	
Egypt		35% [a]	
Jordan		22.5% [a]	
Kuwait		15% [b]	
Libya		13% [a]	
Morocco		52% [a]	100% [a]
Oman	11% [b]		
Saudi Arabia		50% [c]	
Tunisia		30% [a]	100% [a]
UAE - Dubai		25% [b]	

Sources: [a] Timmerberg et al. (2019); [b] Bhatt (2021); [c] Saudi Vision 2030 (2022).

3. Lessons for Reliable Power Systems Beyond Texas

Any blackout of the size that occurred in Texas results in a major review by the U.S. government (FERC-NERC 2021) as well as numerous other reports and academic publications (Busby et al. 2021; Energy Institute of the University of Texas at Austin 2021; Littlechild and Kiesling 2021; Levin et al. 2022; Zhang et al. 2022). Based on these reports and an understanding of the engineering, economics and political economy of power systems, we propose six recommendations (summarized in Table 5) that apply to all types of power systems, including those of the MENA region. We also integrate lessons from other blackouts worldwide into our recommendations. Some of the reviewed blackouts were related to weather events, including high heat and humidity conditions (Victoria State Government 2018), while others resulted from windstorm and floods events (Sheppard and DiSavino 2012). Other non-weather-related blackouts also provide key lessons. In particular, they highlight the importance of reliability analysis and operational rules (such as the N-1 criterion), maintenances practices (such as appropriate tree cutting), software and real-time monitoring and the need for coordination between grid operators (NERC 2004; UCTE 2004a, 2007; ENTSO-E 2015).

Table 5. Summary of our six major recommendations.

1	Low-probability high-impact events, including common-cause failures, are particularly relevant to assessing the resiliency of power systems and should be included in reliability and resiliency analyses.
2	Reliability and resiliency analyses and policies must consider the entire supply chain of electricity, including fuel supply and related infrastructure.
3	Coordination of regulation and market organization of the entire electric-power supply chain is necessary to ensure reliability and resiliency, and fragmented regulation should be avoided.
4	Interconnections and efficient cross-border trading can play a role in limiting power outages, including for power systems with high renewable penetration.
5	Adaptability and energy efficiency can mitigate the societal effects of large power outages.
6	Appropriate rolling blackout procedures, including using new technologies, should be developed to limit the duration of power outages for customers.

Source: Authors.

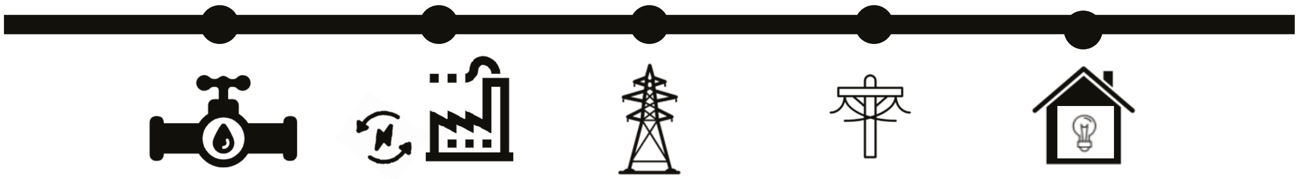
3.1 Reliability and resiliency analyses should consider low-probability high-impact events, including common-cause failures

The 2021 Texas winter storm was an extreme event for which the power sector was not prepared. According to numerous studies, climate change will likely exacerbate the occurrence of extreme high-impact events that have, historically, had a low probability of occurring. Analysis should account for these events (Chandramowli and Felder 2014; Petitet et al. 2021; Felder and Petitet 2021) as well as technical procedures for managing them (such as rolling blackout plans or equipment winterization). To do so, it is necessary to collect and create detailed datasets that are as representative as possible to anticipate future critical events, including ones with low probability.

A power outage can be caused by several independent events or have common-cause failures (Felder 2001). Common-cause failures include severe weather, fuel delivery system failure, a failure of the monitoring and controlling system and malicious actions. Despite being less frequent, common-cause failures can have high impact on power systems, as was the case during the 2021 Texas blackout. Moreover, as illustrated by the 2021 Texas blackout, such common-cause events can also magnify the societal consequences of electricity blackouts. During these events, electricity is highly valuable, and its shortage has dramatic effects, including threatening public health and safety. For these reasons, common-cause failures that also magnify the costs of outages — common-cause, damage-enhancing failures — should be carefully considered in reliability and resiliency analysis.

Figure 4 presents some common-cause events that can affect fuel supply, electricity generation, transmission and distribution networks and load segments. Even though an extreme cold event like the one observed in Texas is unlikely to occur in the MENA region, the Texas blackout emphasizes that common-cause events related to hot weather are also numerous and could severely affect MENA power systems. For example, in Australia, the state of Victoria experienced a blackout during a heat wave in January 2018 mainly caused by overloaded network assets, which was caused by a rise in electricity demand for cooling. Based on a review of weather-related grid events in the U.S., Campbell and Lowry (2012) show that there is an increasing trend in the number of electricity blackout events, which may be explained by grid deterioration but also an increase in weather events.

Figure 4. Common-cause events (non-exhaustive list) related to weather events.



	Fuel supply	Generation	Transmission	Distribution	Load segments
Cold snap	Pipelines freezing	Failures of all types of technologies	Line breaks due to icing		Increased need for electricity for heating Failures of self-generators
Tornado/wind events	Pipelines breaks	Failures of wind turbines	Line breaks due to wind		Disconnected loads due to housing damage
Flood		Failures of hydropower due to high inflows			Disconnected loads due to housing damage
Drought		Failures of thermal and hydropower (electricity-water nexus)	Reduced rating of underground cables		
Heat wave		Failures of all technologies	Reduced rating Damaged lines		Increased need for electricity for cooling Failures of self-generators
Dust storm		Failures of PV			
Firestorm	Damaged equipment				

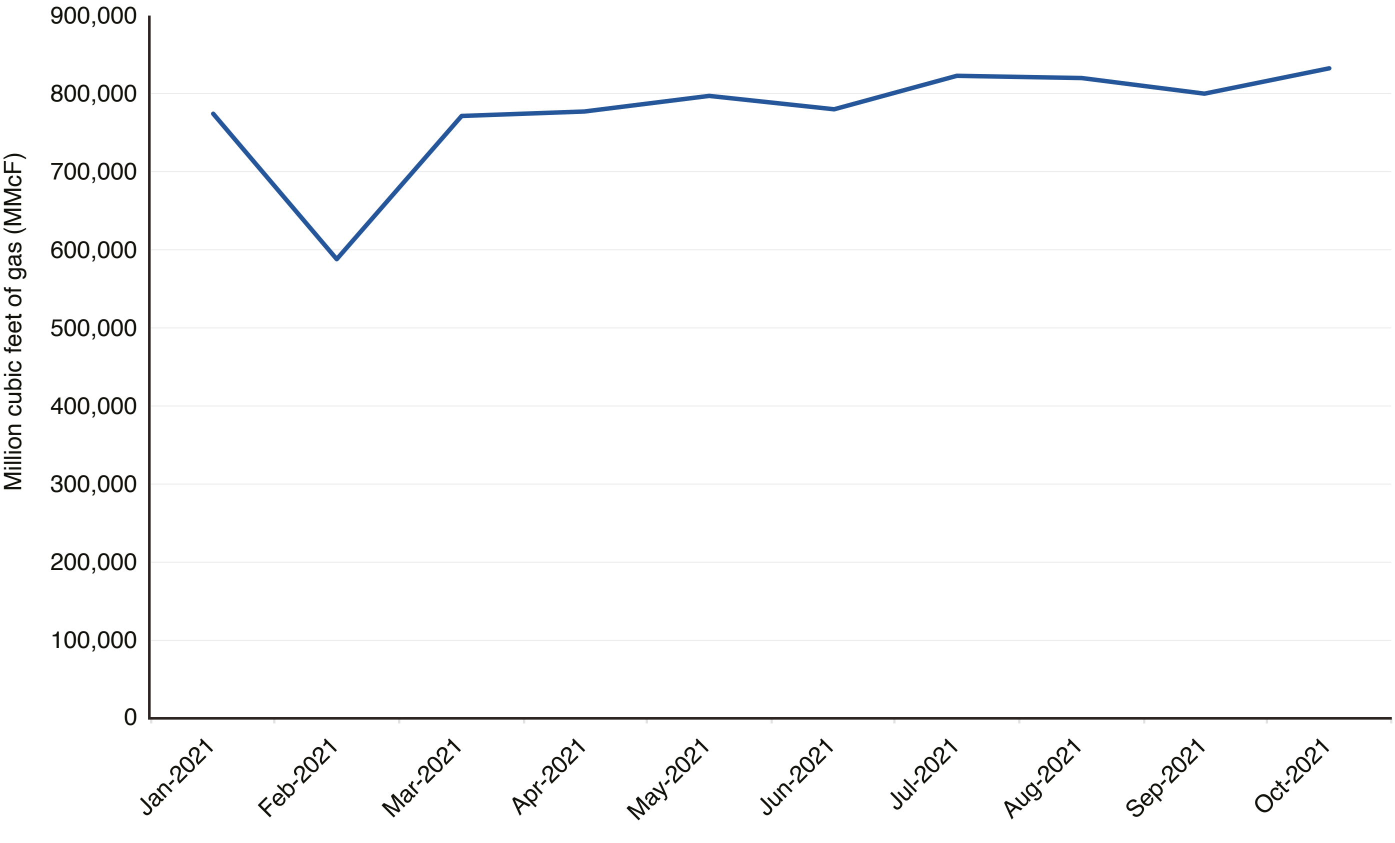
Source: Authors, based on literature review (Campbell and Lowry 2012; Ward 2013; Lubega and Stillwell 2018).

3.2 The entire electricity supply chain matters

In Texas, almost 50% of generation units are fueled by natural gas (FERC-NERC 2021). During its 2021 blackout, the fuel delivery infrastructure failed to supply natural gas to generation units. Natural gas production significantly decreased during the 2021 cold event, which led to many problems for the gas-based generators due to freeze-offs in the suppling pipelines when water and other liquids in the raw natural gas stream froze.

On February 17, 2021, in the central region of the United States, dry natural gas production was as low as 69.7 billion cubic feet per day (bcf/d), down nearly 18.9 bcf/d from the week ending February 13, a decline of 21%. In Texas, natural gas production decreased by almost 45%, falling from 21.3 bcf/d during the week ending February 13 to a daily low of 11.8 bcf/d on February 17 (EIA 2021b). See Figure 5.

Figure 5. Monthly natural gas marketed production in Texas in 2021.



Source: Authors, based on data from EIA (2021b).

At the same time, natural gas is widely used to meet residential heating loads: more than one-third of Texas households rely on natural gas as their primary heating fuel (EIA 2021c). Therefore, natural gas supplies were competing to meet the supply requirements of both generation units and residential heating during this cold weather event, creating a public health crisis. Approximately three in five Texas households use electricity as their primary source for home heating (EIA 2021c). The extremely cold weather increased electricity demand for heating, which also stressed the entire supply chain. Of course, a similar situation could occur during a heat wave, which would increase the demand for air conditioning, which is entirely electricity based.

Reliability standards should be revised to avoid future fuel supply problems, whether natural gas or otherwise, such as requiring natural gas facilities to implement cold-weather preparedness plans based on previous events that have occurred. All types of fuel can be affected by freezing issues, including natural gas as well as coal and oil (FERC-NERC 2021). This would require an in-depth cost-benefit analysis to select the right level of winterization, and other changes in line with social preferences, to account for the tradeoffs identified in Figure 3. Initial estimates suggest that the cost of winterization in Texas is below its benefit to avoid blackout (Golding, Kumar and Mertens 2021). Gas winterization takes time and, according to Bloomberg (Chediak and Malik 2021), could not be ready until 2023, which underscores the importance of reliability planning studies.

Furthermore, protecting critical natural gas infrastructure from the occurrence of manual or automatic shedding is essential because failing to do so will negatively affect the reliability of the grid. This can occur as sudden surges or drops in natural gas pipeline pressure, which can simultaneously shut off multiple natural gas fueled power plants (FERC-NERC 2021). This action is done to protect the pipeline from over pressurization, but it could simultaneously trip multiple natural gas fired plants, thereby exceeding the system’s N-1 capability. In some MENA countries, the gas share in electricity mix could increase in the coming years because of its potential to reduce CO_2 emissions compared to oil-based generation units. This is the case in Saudi Arabia (Saudi Vision 2030 2022), where the shift from oil to gas is a cost-relevant solution for decarbonization (Blasquez et al. 2018). In Jordan, the shift from oil to gas in electricity generation has been happening since 2014, with gas representing 81% of electricity generation in 2019 versus less than 10% in 2014 (IEA 2019).

In addition, grid operators such as ERCOT should be informed about the percentage of generation capacity that can be relied upon during cold weather. In the case of natural gas, generator operators should identify the fuel delivery risks related to their natural gas fuel contracts. This would enable them to plan better and provide more visibility during cold weather operations to anticipate possible problems. It would also provide more lead time to electricity customers who may be disconnected via rolling blackouts.

As previously noted, the 2021 Texas event illustrates to what extent the complete electricity supply chain matters when assessing its reliability. Indeed, it is not sufficient to focus on electricity generation and the network. Instead, the whole supply chain should be prepared for critical events, including fuel supply. Moreover, electricity is one of the vital infrastructure components of current societies, but it is also interlinked to other critical infrastructure beyond the natural gas, such as healthcare, finance, transportation, water systems and information and communications technologies (Kröger 2008; Behnert and Bruckner 2018). In the future, such interrelationships could also expand to other infrastructure like hydrogen and transport through electric vehicles. In the Gulf countries, water production by desalination is critically dependent on electricity (Rambo et al. 2017).

3.3 Importance of regulation and market organization

This blackout also emphasizes the importance of regulation and market organization in helping to avoid outages. Texas liberalized its electricity system in 2002, and since then it has relied solely on energy markets to achieve resource adequacy. Texas is considered, or at least had been considered until its recent blackout, by many economists to be a role model in market design. However, the 2021 Texas blackout questions the ability of the Texas power system's structure to ensure reliability, including the role of electricity markets. In theory, electricity markets with sufficient demand response or/and efficient resource adequacy mechanisms would help to match supply and demand efficiently. As discussed further in section 3.5, smart meters can enable efficient demand response and thus facilitate matching demand and supply.

Despite being considered as a model, Texas is reviewing its market design and regulatory structure. After the February 2021 event, ERCOT temporarily reduced its electricity wholesale price cap from \$9,000/MWh to \$2,000/MWh (below many estimates of the value of lost load), showing how high wholesale prices can be a sensitive issue for policy makers, whereas economists have shown that high electricity prices are necessary during critical events to convey the right price incentives (Boiteux 1949, 1960).

The Texas event also raises the question of efficient coordination of gas and electricity regulation. Despite the recommendations made by the Public Utility Commission (the electricity regulator) after the 2011 cold event to winterize equipment, the Texas Railroad Commission, which oversees Texas gas suppliers, has not yet implemented winterization standards for the gas sector (Griswold and Kling 2021). In addition, incompleteness in the risk trading in liberalized electricity markets (i.e., difficulty hedging risk when investing in electricity assets) has been identified as a reason for the lack of investment in winterization (Mays et al. 2022).

Policy makers still must figure out how to improve the entire market-regulatory structure of gas and electricity to work together to keep the lights on. This is particularly challenging if the regulatory structure of the entire supply chain is fragmented across several regulatory entities.

As the GCC and MENA continue to implement electricity markets and regional trading, they can learn and benefit from experiences worldwide. To ensure the reliability of increasingly interconnected systems in the region, they could consider creating a GCC/MENA entity to coordinate planning studies and inform policy makers. This entity could take lessons from the North American Electric Reliability Corporation (NERC) in the U.S. or the European Network of Transmissions System Operators for Electricity (ENTSO-E) in Europe[6] but tailor them to the region's context and regulatory-market structures. They should also pay attention to the entire electric supply chain and avoid fragmented regulatory structures.

3.4 Interconnections and efficient cross-border trading can limit power outages

ERCOT is a relatively isolated power system with a maximum of 1,220 MW in total import capacity from neighboring regions (FERC-NERC 2021). This import capacity is obtained through two direct current (DC) lines with US Eastern Interconnection through the Southwest Power Pool and two DC lines with Mexico. Power systems interconnected with AC or DC lines do not have the same consequences in terms of reliability or real-time operations. With AC interconnectors, the frequency is shared between neighboring power systems; that is, the systems are synchronous, allowing for one system to automatically support the other during reliability events. However, there is also a risk that a blackout in one system could cause one in the other. With DC interconnectors only, that is, the systems are asynchronous, grid operators decide on the power flow's direction and magnitude across the interconnection. This enables a blackout in one system to be isolated from its neighbor, but it reduces the ability of its neighbor to provide support in real time (Kundur 2012). Moreover, DC lines have higher nominal capacity, but they can experience outages more frequently than AC lines, resulting in significant energy imbalances (Ye et al. 2022). In both cases, detailed plans between the interconnected regions must be agreed upon by grid operators before a critical event happens while carefully considering the AC or DC nature of the interconnectors.

The Texan interconnection capacities of 1,220 MW are low compared to the size of the power system, with a peak load above 70 GW and a generation capacity of 123 GW. ERCOT's total installed generation capacity includes 31 MW of wind power, 6 MW of solar, 64 MW of gas and 15 GW of coal (FERC-NERC 2021). To estimate the level of interconnection of a power system, the total import capacity can be compared to the system's peak load or the total installed generation capacity. In 2021, for Texas, the ratio of interconnection to peak load[7] was 1.6%. The ratio using generation capacity was 1.0%.

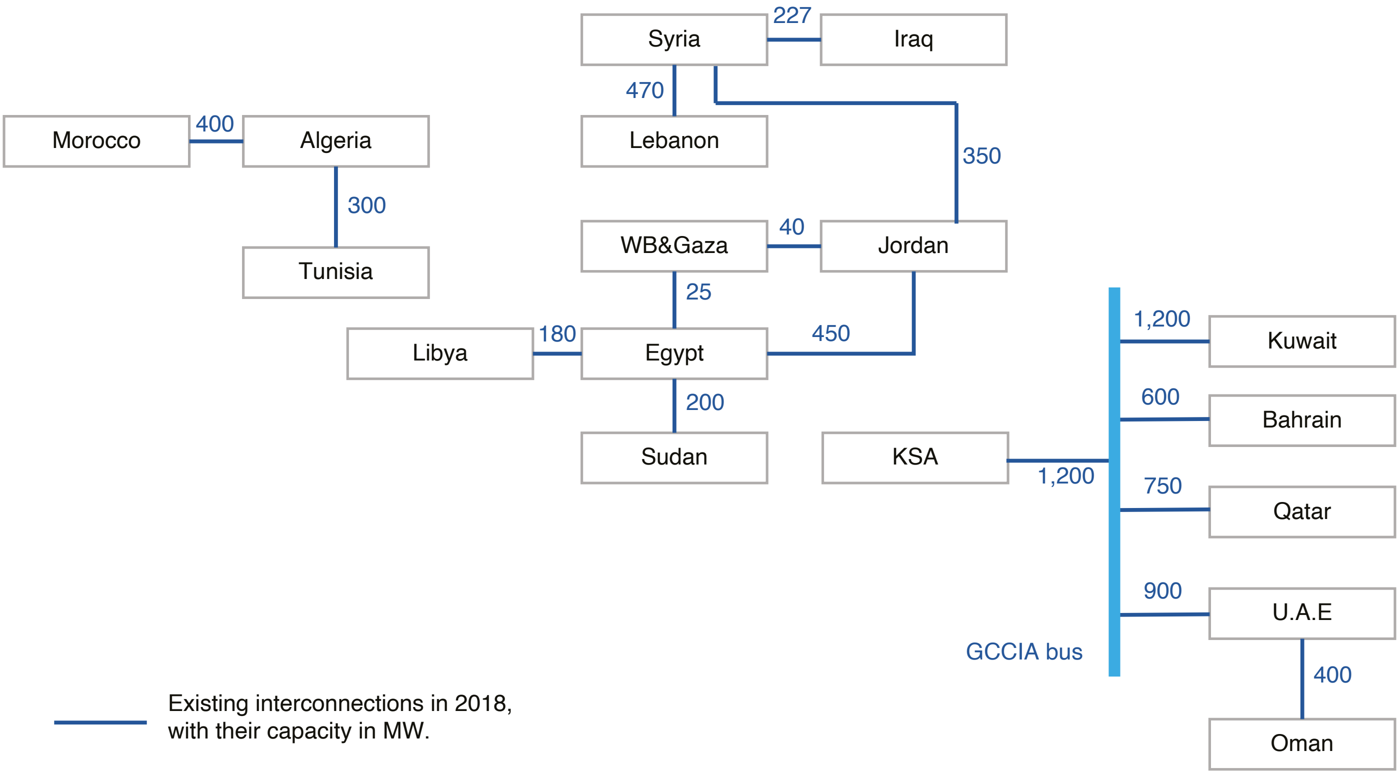
In Europe, the electricity interconnection target, defined as import capacity over installed generation capacity, to be achieved by each member state by 2030, has been increased from 10% to 15%, (European Council 2014).[8] The Expert Group on electricity interconnection targets (European Commission 2017) has confirmed that the benefits exceed the cost of increasing the European interconnection target to deal with the expected renewable penetration. In 2020, all but four European countries (Cyprus, Spain, Poland and the United Kingdom) had reached the interconnection target of 10% (Legislative Train 2022).

Power systems in the MENA region are interconnected, forming three distinct areas, as illustrated in Figure 6. The western area is composed of Morocco, Algeria and Tunisia, which are interconnected by AC lines. The central area encompasses Libya, Egypt, Sudan, Jordan, West Bank & Gaza, Lebanon, Syria and Iraq. The eastern region corresponds to the Gulf countries, namely Saudi Arabia, Oman, the U.A.E., Qatar, Bahrain and Kuwait. These countries are mostly interconnected through the GCC Interconnection Authority (GCCIA) bus with DC lines. Yemen has no interconnection with neighboring countries.

Based on 2018 historical data from the World Bank (2021), Table 6 estimates the interconnection level for the MENA countries, and Figure 7 graphically illustrates the interconnection level to generation capacity. It shows that some of the small power systems already have an interconnection level higher than 15%, such as Bahrain, Jordan, Lebanon and Syria. All other MENA countries have an interconnection level below 10%.

The interconnection level of MENA countries is expected to increase in the following years as new interconnectors will come online, such as the 3 GW interconnector between Egypt and Saudi Arabia. These projects will also connect the western, central, and eastern areas.

Figure 6. Existing cross-border interconnections in the MENA region.



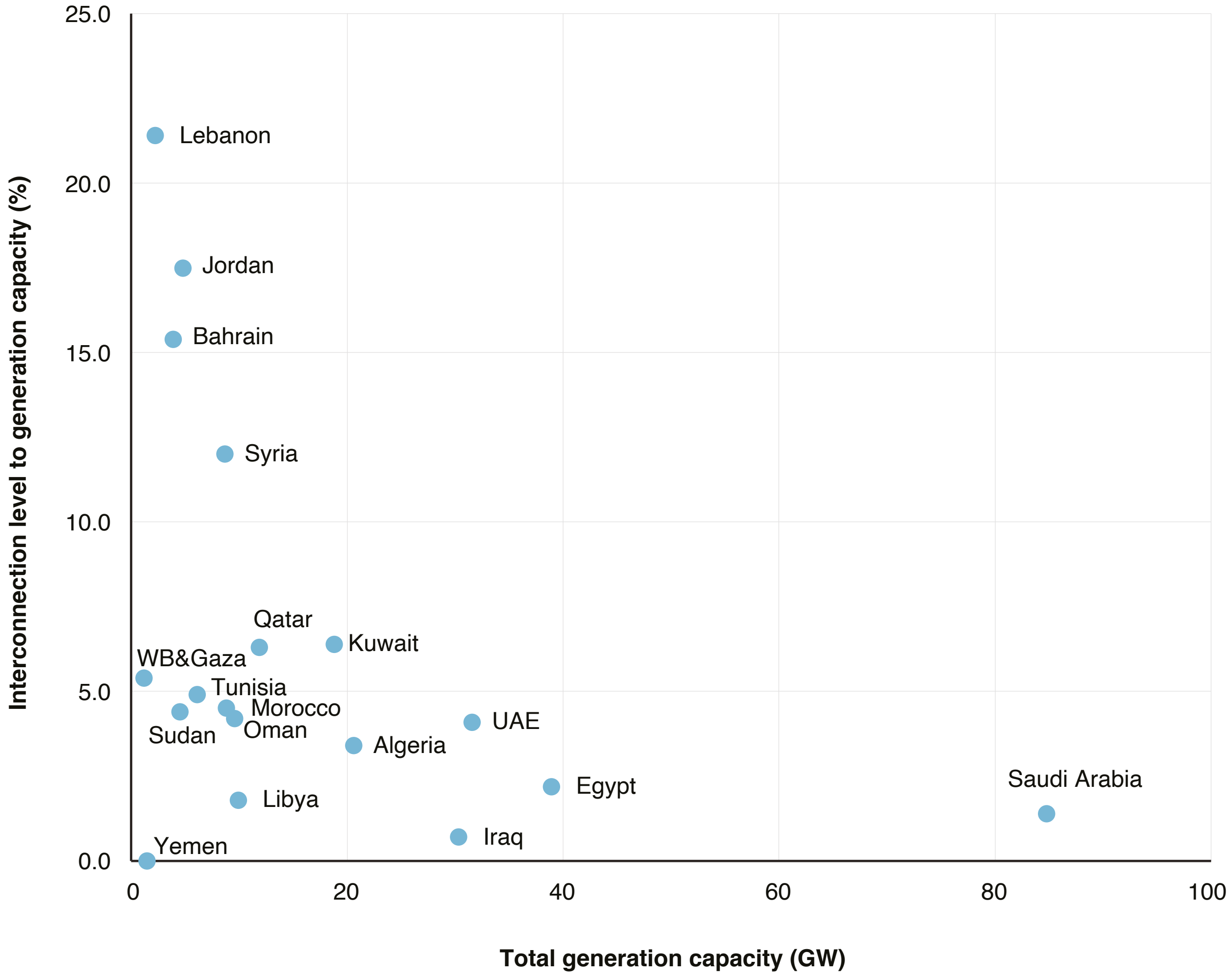
Source: Authors, based on World Bank (2021).

Table 6. Estimated interconnection level for MENA countries in 2018.

	Peak demand GW	Total generation capacity GW	Total interconnector capacity GW	Interconnection to peak load %	Interconnection to total generation capacity %
Algeria	12.9	20.6	0.70	5.4	3.4
Bahrain	3.6	3.9	0.60	16.7	15.4
Egypt	31.6	38.9	0.86	2.7	2.2
Iraq	24	30.3	0.23	0.9	0.7
Jordan	3.6	4.8	0.84	23.3	17.5
Kuwait	13.6	18.8	1.20	8.8	6.4
Lebanon	3.6	2.2	0.47	13.1	21.4
Libya	5	9.9	0.18	3.6	1.8
Morocco	6.5	8.8	0.40	6.2	4.5
Oman	7.3	9.6	0.40	5.5	4.2
West Bank and Gaza	1.4	1.2	0.07	4.6	5.4
Qatar	7.8	11.9	0.75	9.6	6.3
Saudi Arabia	69.9	84.8	1.20	1.7	1.4
Sudan	3.2	4.5	0.20	6.3	4.4
Syria	5.7	8.7	1.05	18.4	12.0
Tunisia	3.8	6.1	0.30	7.9	4.9
UAE	23.4	31.6	1.30	5.6	4.1
Yemen	1.4	1.5	0.00	0.0	0.0

Source: Peak demand, total generation capacity and interconnector capacity (World Bank 2021).

Figure 7. Interconnection level to generation capacity, estimated on 2018 data.



Source: Authors, based on data from World Bank (2021).

The interconnection level is useful for quantifying the maximum extent to which a power system may be supported by neighboring regions and thus can rely on imports to meet its internal demand. However, this maximum import capacity may not be reached during critical events for several reasons. Import capacity can be limited during critical events because of failures in the internal or cross-border transmission network. Neighboring regions can also face similar critical events simultaneously, as was the case in Texas in February 2021 (FERC-NERC 2021). In this case, grid operators could decide to reduce exports and prioritize matching their own electricity demand. Anticipating how cross-border exchanges would be done in case of simultaneous critical events in neighboring regions is a key element of an interconnected power system's reliability, and thus should be agreed upon.

3.5 Adaptability and energy efficiency can mitigate effects of large power outages

The consequences of the 2021 Texas power outage were devastating for residential consumers because of the event's duration and the lack of solutions for replacing electricity, particularly for heating.

However, in the long term, strategies could be developed to mitigate the effects of power outages for consumers. These could include actions to adapt power systems (we refer to this as the "adaptability" of power systems), such as improving housing insulation and building warming/cooling centers to be used in case of emergency, particularly in those areas whose distribution systems are not designed for rotating blackouts. Increasing energy efficiency, particularly through better building insulation, would decrease the consequences of such events. More broadly, the adaptability of power systems should be considered and supported by policy makers as a levy to reduce the consequences of power outages (Felder and Petitet 2021).

As previously noted, smart meters can also mitigate the impacts of large power outages by providing real time and location-adjusted information to consumers, and by allowing real-time monitoring of distribution network near load. ERCOT has approximately 11 million deployed smart meters (Energy Institute of the University of Texas at Austin 2021), corresponding to roughly 40% of its customers. While smart metering will continue to be deployed, current rules in Texas limit access to data and improvements are required to allow access to real-time data (Walton 2020).

In the MENA region, smart meters are deployed and are expected to play a role in improved management of electricity demand. Saudi Arabia completed the deployment of 10 million smart meters to all electricity customers in April 2021 (Arab News 2021; Hasan, Mansouri and Al-Shehri 2021). In 2021, Oman also announced that 1.2 million smart meters would be installed within five years, in line with Oman Vision 2040 (Utilities Middle East 2021).

3.6 Appropriate rolling blackout procedures can limit the duration of power outages for customers

During the 2021 blackout, residential consumers faced electricity outages in Texas for extended periods during extremely cold weather. Even having electricity for a few hours each day would have been life saving for some households.

Grid operators research and define procedures (and install adequate equipment) to implement rolling blackouts for end-consumers while ensuring operation security for transmission and distribution networks. These studies and actions, which should occur before a blackout, influence the way rotating blackouts can be performed in real-time in case of an event such as the 2021 winter storm in Texas. FERC-NERC 2021 has identified some technical difficulties that prevented ERCOT from efficiently performing rotating blackouts due to distribution system limitations. Particularly, low voltage and underfrequency protection schemes in place in Texas limited the rolling options available to the system operators. Whether similar technical challenges exist in the MENA region should be evaluated and addressed as appropriate.

4. Conclusion

The Texas blackout in February 2021 has refocused attention on the importance of reliability and resiliency in electric power systems. One year after this event, reports and analyses have improved our understanding of the underlying causes and lessons to be learned. Building on this and other major blackouts, we provide six major recommendations for policy makers to enhance the reliability and resiliency of power systems. These recommendations apply not only to liberalized power systems, like the one in Texas, but also to all types of power systems, including those in the MENA region.

First, these lessons emphasize the need for enhanced attention on threats to reliability and resiliency from common-cause events such as severe weather and for improved data sets and models that can consider new power system technologies such as variable and intermittent renewables. Second, the resiliency and reliability of power systems requires an integrated approach that accounts for the entire electricity supply chain and its impacts on critical societal functions such as public safety, health care, communications, finance and transportation. Finally, power systems' reliability and resiliency attributes also depend on regional and international interconnections, cross-border trading and associated regulatory structures.

Endnotes

[1] The value of loss load (VoLL) used to estimate this figure was based on 2019 data of $6,733/MWh for industrials and $117.6/MWh for households. Note that the VoLL estimated for households seems low with respect to the effects of the 2021 blackout, characterized by the dramatic social consequences and long duration.

[2] ERCOT stands for the Electric Reliability Council of Texas. It is the entity that administers the wholesale electricity market, which covers approximately 90% of Texas' electricity load (FERC-NERC 2021).

[3] This tradeoff conceptually applies to other non-power systems, such as transportation, healthcare, etc.

[4] Some renewable energy resources, such as hydroelectric facilities, biomass, biofuel, geothermal and concentrating solar power, are dispatchable, although their availability depends on local conditions.

[5] The ability of a power system to continue to operate reliably when any component fails. "N" refers to the number of generation and transmission components, and "N-1" refers to the ability to withstand the failure of one component and recover sufficiently quickly before another component fails.

[6] NERC and ENTSO-E have similar roles in carrying out reliability studies and providing recommendations to improve power system operations.

[7] In 2021, Texas' peak load was 76.8 GW (FERC-NERC 2021).

[8] Although the 10% target for 2020 was estimated based on the ratio between the net transfer capacity of interconnectors and total production capacity, the new interconnection target of 15% is evaluated through a combination of three sub-criteria: average of wholesale price differentials lower than 2 euro/MWh; ratio between the total nominal transmission capacity of interconnectors and peak load higher than 30%; and the ratio between the total nominal transmission capacity of interconnectors and installed renewable capacities higher than 30% (European Commission 2017).

References

Arab News. 2021. “SEC Deploys 10m Smart Meters in Move Toward Digital.” Accessed April 13. https://www.arabnews.com/node/1842396/corporate-news

Behnert, Marika, and Thomas Bruckner. 2018. “Causes and Effects of Historical Transmission Grid Collapses and Implications for the German Power System.” *Institute for Infrastructure and Resources Management*. No. 03/2018. Leipzig: Institute for Infrastructure and Resources Management. http://hdl.handle.net/10419/190501

Bhatt, Yagyavalk. 2021. “Renewable Energy Deployment to Stimulate Energy Transition in the Gulf Cooperation Council.” *Renewable Energy Transition in Asia: Policies, Markets and Emerging Issues* (2021):161–83. https://doi.org/10.1007/978-981-15-8905-8_8

Billinton, Roy, and Ronald N. Allan. 1984. “Power-system Reliability in Perspective.” *Electronics and Power* 30(3):231–6. https://doi.org/10.1049/ep.1984.0118

Blazquez, Jorge, Baltasar Manzano, Lester C. Hunt, and Axel Pierru. 2018. “The Value of Saving Oil in Saudi Arabia.” KAPSARC Discussion Paper. https://doi.org/10.30573/KS--2018-DP030

Blunt, Katherine, and Charles Passy. 2021. “In Texas, Winter Storm Forces Rolling Power Outages as Millions are Without Electricity.” *Wall Street Journal*, February 16. Accessed February 20, 2022. https://www.wsj.com/articles/winter-storm-forces-rolling-power-outages-in-texas-11613407767

Boiteux, Marcel. 1949. “La Tarification des Demandes en Pointe.” *Revue Générale de l’Electricité* 58:157–79.

Boiteux, Marcel. 1960. “Peak-load Pricing.” *The Journal of Business* 33(2):157–79.

Busby, Joshua W., Kyri Baker, Morgan D. Bazilian, Alex Q. Gilbert, Emily Grubert, Varun Rai, Joshua D. Rhodes, Sarang Shidore, Caitlin A. Smith, and Michael E. Webber. 2021. “Cascading Risks: Understanding the 2021 Winter Blackout in Texas.” *Energy Research & Social Science* 77:102106. https://doi.org/10.1016/j.erss.2021.102106

Campbell, Richard J., and Sean Lowry. 2012. *Weather-related Power Outages and Electric System Resiliency*. Washington, DC: Congressional Research Service, Library of Congress.

Carlson, Tucker. 2021. “The great Texas climate catastrophe is heading your way.” *Fox News*, February 15. Accessed February 20, 2022. https://www.foxnews.com/opinion/tucker-carlson-texas-green-new-deal-climate-catastrophe

Chandramowli, Shankar, and Frank A. Felder. 2014. “Climate Change and Power Systems Planning—Opportunities and Challenges.” *The Electricity Journal* 27(4):40–50. https://doi.org/10.1016/j.tej.2014.04.002

Chediak, Mark, and Naureen S. Malik. 2021. “Texas Isn’t Ready for Another Deep Freeze.” *Bloomberg*, October 30. Accessed February 20, 2022. https://www.bloomberg.com/news/articles/2021-10-30/texas-energy-grid-remains-vulnerable-to-winter-blackouts

Electric Power Research Institute (EPRI). 2022. *Enhancing Energy System Reliability and Resiliency in a Net-zero Economy*. Palo Alto, CA: EPRI. http://mydocs.epri.com/docs/public/EPRI-Report-EnhancingEnergySystemReliability-20210804.pdf

Energy Information Administration (EIA). 2021a. “Hourly Electric Grid Monitor.” https://www.eia.gov/electricity/gridmonitor/dashboard/custom/pending

Energy Information Administration (EIA). 2021b. “Texas Natural Gas Production Fell by Almost Half During Recent Cold Snap.” February 25. https://www.eia.gov/todayinenergy/detail.php?id=46896

Energy Information Administration (EIA). 2021c. “Texas - State Energy Profile Analysis.” Last modified April 15. https://www.eia.gov/state/analysis.php?sid=TX

Energy Information Administration (EIA). 2022. “Glossary.” https://www.eia.gov/tools/glossary/index.php?id=R

Energy Institute of the University of Texas at Austin. 2021. “The Timeline and Events of the February 2021 Texas Electric Grid Blackouts.” https://energy.utexas.edu/sites/default/files/UTAustin%20%282021%29%20EventsFebruary2021TexasBlackout%2020210714.pdf

European Commission. 2017. “Report of the Commission Expert Group on Electricity Interconnection Targets: Towards a Sustainable and Integrated Europe.” https://ec.europa.eu/energy/sites/ener/files/documents/report_of_the_commission_expert_group_on_electricity_interconnection_targets.pdf

European Council. 2014. “Conclusions of the European Council of 23-24 October 2014.” https://www.consilium.europa.eu/uedocs/cms_data/docs/pressdata/en/ec/145397.pdf

European Network of Transmission System Operators for Electricity (ENTSO-E). 2015. “Report on Blackout in Turkey on 31st March 2015, Final Version 1.0.” https://eepublicdownloads.entsoe.eu/clean-documents/SOC%20documents/Regional_Groups_Continental_Europe/20150921_Black_Out_Report_v10_w.pdf

Federal Energy Regulatory Commission (FERC) and North American Electric Reliability Corporation (NERC) (FERC-NERC). “The February 2021 Cold Weather Outages in Texas and the South Central United States.” https://ferc.gov/media/february-2021-cold-weather-outages-texas-and-south-central-united-states-ferc-nerc-and

Felder, Frank A. 2001. "’An Island of Technicality in a Sea of Discretion’: A Critique of Existing Electric Power Systems Reliability Analysis and Policy." *The Electricity Journal* 14(3):21–31. https://doi.org/10.1016/S1040-6190(01)00183-X

Felder, Frank A., and Amro Elshurafa. 2021. “What Lessons Can KSA Learn from the Texas Blackouts?” KAPSARC Podcast no. 8. https://www.kapsarc.org/podcast/what-lessons-can-ksa-learn-from-the-texas-blackouts/

Felder, Frank A., and Marie Petitet. 2021. “Renewables, Reliability and Efficiency in Electricity Markets.” KAPSARC Discussion Paper. https://www.kapsarc.org/research/publications/renewables-reliability-and-efficiency-in-electricity-markets/

Griswold, Niki, and Karina Kling. 2021. “Winter is Coming: As Texans Fear Future Blackouts, Energy Regulators Work to Ease Concerns.” *Spectrum News*, November 11. https://spectrumlocalnews.com/tx/south-texas-el-paso/news/2021/11/11/winter-is-coming--as-texans-fear-future-blackouts--energy-regulators-work-to-ease-concerns-----

Golding, Garrett, Anil Kumar, and Karel Mertens. 2021. “Cost of Texas’ 2021 Deep Freeze Justifies Weatherization.” Federal Reserve Bank of Dallas, April 15. https://www.dallasfed.org/research/economics/2021/0415?topics=Texas+Economy

Hasan, Shahid, Noura Mansouri, and Thamir Al-Shehri. 2021. “Beyond Smart Meters”. KAPSARC Instant Insight. https://www.kapsarc.org/research/publications/beyond-smart-meters/

References

Hauser, Christine, and Edgar Sandoval. 2021. “Death Toll from Texas Winter Storm Continues to Rise.” *The New York Times*, July 14. https://www.nytimes.com/2021/07/14/us/texas-winter-storm-deaths.html

International Energy Agency (IEA). 2019. “Jordan Key Energy Statistics.” Available at https://www.iea.org/countries/jordan

Kahnamouei, Ali Shakeri, Tohid Ghanizadeh Bolandi, and M-R. Haghifam. 2017. “The Conceptual Framework of Resilience and Its Measurement Approaches in Electrical Power Systems.” Paper presented at the IET International Conference on Resilience of Transmission and Distribution Networks (RTDN 2017), Birmingham, UK, September 26–28. https://doi.org/10.1049/cp.2017.0335

Kröger, Wolfgang. 2008. “Critical Infrastructures at Risk: A Need for a New Conceptual Approach and Extended Analytical Tools.” *Reliability Engineering & System Safety* 93(12):1781–87. https://doi.org/10.1016/j.ress.2008.03.005

Kundur, Prabha. 2012. Power System Stability and Control. Third Edition. Boca Raton, FL: CRC Press.

Legislative Train. 2022. “Communication on Achieving a 15% Electricity Interconnection Target.” https://www.europarl.europa.eu/legislative-train/api/stages/report/current/theme/resilient-energy-union-with-a-climate-change-policy/file/communication-on-achieving-a-15-electricity-interconnection-target

Levin, Todd, Audun Botterud, W. Neal Mann, Jonghwan Kwon, and Zhi Zhou. 2022. “Extreme Weather and Electricity Markets: Key Lessons from the February 2021 Texas Crisis.” *Joule* 6(1):1–7. https://doi.org/10.1016/j.joule.2021.12.015

Littlechild, Stephen, and Lynne Kiesling. 2021. “Hayek and the Texas Blackout.” *The Electricity Journal* 34(6):106969. https://doi.org/10.1016/j.tej.2021.106969

Lubega, William Naggaga, and Ashlynn S. Stillwell. 2018. “Maintaining Electric Grid Reliability Under Hydrologic Drought and Heat Wave Conditions.” *Applied Energy* 210: 538–49. https://doi.org/10.1016/j.apenergy.2017.06.091

Mays, Jacob, Michael Craig, L. Lynne Kiesling, Joshua Macey, Blake Shaffer, and Han Shu. 2022. “Private Risk and Social Resilience in Liberalized Electricity Markets.” *Joule* 6(2):369-80. https://doi.org/10.1016/j.joule.2022.01.004

North American Electric Reliability Corporation (NERC). 2004. “Technical Analysis of the August 14, 2003, Blackout: What Happened, Why, and What Did We Learn? Report to the NERC Board of Trustees by the NERC Steering Group.” https://www.nerc.com/docs/docs/blackout/NERC_Final_Blackout_Report_07_13_04.pdf

North American Electric Reliability Corporation (NERC). 2007. “Definition of ‘Adequate Level of Reliability.’” https://www.nerc.com/docs/pc/Definition-of-ALR-approved-at-Dec-07-OC-PC-mtgs.pdf

North American Electric Reliability Corporation (NERC). 2021a. “Announcement – Summer Assessment Warns of Potential Energy Shortfalls.” https://www.nerc.com/news/Headlines%20DL/SRA%20Announcement%2026MAY21.pdf

North American Electric Reliability Corporation (NERC). 2021b. “Glossary of Terms Used in NERC Reliability Standards.” Version updated June 28. https://www.nerc.com/files/glossary_of_terms.pdf

Panteli, Mathaios, and Pierluigi Mancarella. 2015. “The Grid: Stronger, Bigger, Smarter?: Presenting a Conceptual Framework of Power System Resilience.” *IEEE Power and Energy Magazine* 13(3):58–66. https://doi.org/10.1109/MPE.2015.2397334

Petitet, Marie, Burçin Ünel, Rolando Fuentes, and Frank A. Felder. 2021. “Climate and Power System Reliability in the Aftermath of the Texas Blackouts.” *IAEE Energy Forum* Third Quarter 2021. https://www.iaee.org/en/publications/newsletterdl.aspx?id=958

Phillips, Stephanie. 2019. “Federal Regulation for a Resilient Electricity Grid.” Ecology Law Quarterly 46(2019)(2):415.

Plotnek, Jordan J., and Jill Slay. 2001. “Power Systems Resilience: Definition and Taxonomy with a View Towards Metrics.” *International Journal of Critical Infrastructure Protection* 33:100411. https://doi.org/10.1016/j.ijcip.2021.100411

Rambo, Khulood A., David M. Warsinger, Santosh J. Shanbhogue, John H. Lienhard V, and Ahmed F. Ghoniem. 2017. “Water-energy Nexus in Saudi Arabia.” *Energy Procedia* 105:3837–43. https://doi.org/10.1016/j.egypro.2017.03.782

REN21. 2021. “Renewables 2021 Global Status Report.” https://www.ren21.net/wp-content/uploads/2019/05/GSR2021_Full_Report.pdf

Reuters Staff. 2021. “Fact check: The Causes for Texas’ Blackout Go Well Beyond Wind Turbines.” *Reuters*, February 19. https://www.reuters.com/article/uk-factcheck-texas-wind-turbines-explain-idUSKBN2AJ2EI

Saudi Vision 2030. 2022. “Renewable Energy Sector in the Kingdom.” Accessed February 20, 2022. https://www.vision2030.gov.sa/thekingdom/explore/energy/

Seneviratne, Sonia, Neville Nicholls, David Easterling, Clare Goodess, Shinjiro Kanae, James Kossin, and Yali Luo, Jose Marengo, Kathleen McInnes, Mohammad Rahimi, Markus Reichstein, Asgeir Sorteberg, Carolina Vera, and Xuebin Zhang. 2012. “Changes in Climate Extremes and Their Impacts on the Natural Physical Environment.” In *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, edited by C.B. Field, V. Barros, T.F. Stocker, D. Qin, D.J. Dokken, K.L. Ebi, M.D. Mastrandrea, K.J. Mach, G.-K. Plattner, S.K. Allen, M. Tignor, and P.M. Midgley, 109–230. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change (IPCC). Cambridge, UK: Cambridge University Press. https://library.harvard.edu/sites/default/files/static/collections/ipcc/docs/AR5_WG2_n_SREX_chapters_and_review/ii_SREX/c_Final_draft_SREX/SREX-Chap3_FINAL.pdf

Sheppard, David, and Scott DiSavino. 2012. “Superstorm Sandy Cuts Power to 8.1 Million Homes.” *Reuters* U.S. News, October 30. https://www.reuters.com/article/us-storm-sandy-powercuts-idUSBRE89T10G20121030

Stott, Peter. 2016. “How Climate Change Affects Extreme Weather Events.” *Science* 352(6293):1517–18. https://doi.org/10.1126/science.aaf7271

Timmerberg, Sebastian, Anas Sanna, Martin Kaltschmitt, and Matthias Finkbeiner. 2019. “Renewable Electricity Targets in Selected MENA Countries–Assessment of Available Resources, Generation Costs and GHG emissions.” *Energy Reports* (5):1470–87. https://doi.org/10.1016/j.egyr.2019.10.003

References

Umunnakwe, A., H. Huang, K. Oikonomou, and K. R. Davis. 2021. “Quantitative Analysis of Power Systems Resilience: Standardization, Categorizations, and Challenges.” *Renewable and Sustainable Energy Reviews* 149:111252. https://doi.org/10.1016/j.rser.2021.111252

Union for the Co-ordination of the Transmission of Electricity (UCTE). 2004a. “Final Report of the Investigation Committee on the 28 September 2003 Blackout in Italy.” https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/ce/otherreports/20040427_UCTE_IC_Final_report.pdf

Union for the Co-ordination of the Transmission of Electricity (UCTE). 2004b. “Operation Handbook - Glossary.” https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/entsoe/Operation_Handbook/glossary_v22.pdf

Union for the Co-ordination of the Transmission of Electricity (UCTE). 2007. “Final Report: System Disturbance on 4 November 2006.” https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/publications/ce/otherreports/Final-Report-20070130.pdf

Utilities Middle East Staff. 2021. “Oman to Roll Out 1.2 Million Smart Meters in Five Years.” Utilities Middle East, April 15. https://www.utilities-me.com/news/17121-oman-to-roll-out-12-million-smart-meters-in-five-years

Victoria State Government, Environment, Land, Water and Planning. 2018. “Post Event Review – Power Outages 28 & 29 January 2018.” https://www.energy.vic.gov.au/__data/assets/pdf_file/0021/328260/Post-Event-Review-Power-Outages-28-and-29-January-2018.pdf

Walton, Robert. 2020. “Texas Regulators Approve New Smart Meter Rules, Limiting Access to Real-Time Data.” *Utility Dive*, Updated April 22. https://www.utilitydive.com/news/texas-regulators-approve-new-smart-meter-rules-limiting-access-to-real-tim/576093/

Ward, David M. 2013. “The Effect of Weather on Grid Systems and the Reliability of Electricity Supply.” *Climatic Change* 121(1):103–13. https://doi.org/10.1007/s10584-013-0916-z

World Bank. 2021. “The Value of Trade and Regional Investments in the Pan-Arab Electricity Market: Integrating Power Systems and Building Economies.” Washington, DC: World Bank. https://openknowledge.worldbank.org/handle/10986/36614

Ye, Chengjin, Libang Guo, Yi Ding, Ming Ding, Peng Wang, and Lei Wang. 2022. “Reliability Assessment of Interconnected Power Systems with HVDC Links Considering Frequency Regulation Process.” *Journal of Modern Power Systems and Clean Energy*. https://doi.org/10.35833/MPCE.2021.000491

Zappa, William, Martin Junginger, and Machteld van den Broek. 2019. “Is a 100% Renewable European Power System Feasible by 2050?” *Applied Energy* 233:1027–50. https://doi.org/10.1016/j.apenergy.2018.08.109

Zhang, Guanglun, Haiwang Zhong, Zhenfei Tan, Tong Cheng, Qing Xia, and Chongqing Kang. 2022. “Texas electric power crisis 2021 warns of a new blackout mechanism.” *CSEE Journal of Power and Energy Systems* 8(1):1–9. https://doi.org/10.17775/CSEEJPES.2021.07720

Notes

Notes

Notes

About the Authors

Marie Petitet

Marie is a senior research associate in the Energy Transitions and Electric Power program at KAPSARC. Her current research focuses include power system modeling and market designs for energy transitions. Prior to joining KAPSARC, Marie worked as a research engineer within the Research and Development (R&D) unit of the utility group EDF in Paris, France. During her EDF journey, she worked on long-term and short-term electricity market design, transmission grids at the European scale and smart-charging opportunities for electric vehicles.

Marie holds a Ph.D. in Economics from Dauphine University, PSL (France), an M.Sc. in environmental and energy economics from École des Ponts ParisTech (France) and an M.Sc. in engineering from ENSTA Institut Polytechnique de Paris (France).

Khalid AlHadhrami

Khalid is an analyst in the Energy Transitions and Electric Power program at KAPSARC. He is an electrical power and machines engineer with a bachelor's degree from the Department of Electrical Engineering at King Abdulaziz University. He worked on several projects at King Abdulaziz University and during his internship at KAPSARC related to renewables and the electric power systems field, most of which were within the distribution system network.

Frank A. Felder

Frank is an engineer, energy policy analyst and Program Director for Energy Transitions and Electric Power. Prior to joining KAPSARC, Frank was a Research Professor at the School of Planning and Public Policy at Rutgers University, Director of the Rutgers Energy Institute and Director of the Center for Energy, Economics and Environmental Policy. In those roles, he conducted original and applied research in the areas of electric power system modeling, clean energy policies and climate change for academic foundations, government agencies and energy utilities. He has also worked as an economic consultant and nuclear engineer.

About the Project

This paper is part of the project “Innovations in electricity markets, network regulations, low-carbon investments and technologies” under KAPSARC’s Energy Transitions and Electric Power program. This project aims to provide insights on the transformation of the Saudi electricity sector. This transformation is characterized by a willingness to increase the share of renewables and replace liquid fuels with natural gas. It must also ensure fiscal balance, expand electricity exports, produce green hydrogen and diversify the Saudi economy through localization. This project provides insights into this transition by discussing and learning from electricity markets worldwide.

KAPSARC

مركز الملك عبدالله للدراسات والبحوث البترولية
King Abdullah Petroleum Studies and Research Center

www.kapsarc.org