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A systematic review on power system resilience from the perspective of generation, network, and load

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ABSTRACT

Power systems are the backbone of modern society, but high-impact and low-probability natural disasters pose unprecedented challenges to power systems in recent years. Power systems consist of generation, networks, and loads, which have their own characteristics. Different sectors need to various responses and strategies in the face of natural disasters. This paper presents a systematic review on power system resilience from four dimensions: (1) Impact analysis. In this dimension, typical disaster-related power outages are quantitatively analyzed, and the impacts of the events on the power systems from the perspective of generation/networks/loads are qualitatively analyzed. (2) Impact quantification. The quantification metrics of the impacts of different events on generation, networks, and loads are systematically reviewed. These systematical quantification metrics are essential prerequisites for resilience improvements. (3) Resilience improvement. Adaptation options from the component-level perspectives are first introduced, and then the optimal strategies from the system-level perspectives are presented. Various power sources have different power production characteristics against different kinds of natural disasters, and coordinated scheduling of different power sources is an effective means to improve generation resilience. System networks are important to bridge generation and loads, and they need to have strong resilience in the face of varying and uncertain impacts caused by natural disasters with system hardening, reconfiguration implementation, microgrid formulation, etc. Loads are becoming more smart and responsive, and these smart/responsive loads have outstanding potential regulating abilities for improving power system resilience. (4) Future research directions with regard to power system resilience improvements are discussed.

1. Introduction

Extreme weather events, e.g., typhoons, wind/ice storms, hurricanes, extreme precipitation, heat waves, and drought, occur with higher frequency compared to the past. A power system has a wide geographical area, and many of devices in the power system are directly exposed in the external natural environment or undirectly impacted by the external natural environment [1]. Devices are vulnerable to extreme weather events, which could result in unexpected power outages. For example, the Southwest Powerlink transmission system in California was out of service because of wildlifes in 2007, and about 35 miles of lines and 1500 utility poles were damaged [2]; The ice storm in 2013 caused more than one million people in U.S. and Canada in blackout [3]; In 2012, over eight million users lost their power due to Hurricane Sandy, which caused 7000 transformers and 15,200 poles damaged. The severe weather-related outages have driven many organizations and governments to realize the necessary of power system resilience against extreme weather events. In June 2011, the U.S. government released a report named as A Policy Framework for the 21st Century Grid, which emphasized the importance of power system resilience in consideration of increased extreme weather events [4]. Many other organizations, e.g., the House of Lords in the United Kingdom and the United States Electric Power Research Institute, have also released their own reports to emphasize the significance of power system resilience. According to the conceptual framework of power system resilience [5], appropriate strategies during three stages, i.e., prior to the event, during the event and after the event, should be considered. Several resilience curves based on these stages are reviewed in [6], and proactive resilience strategies against natural disasters are also discussed. Furthermore, many studies have focused on power system resilience in three stages from the perspective of state evaluation [7],

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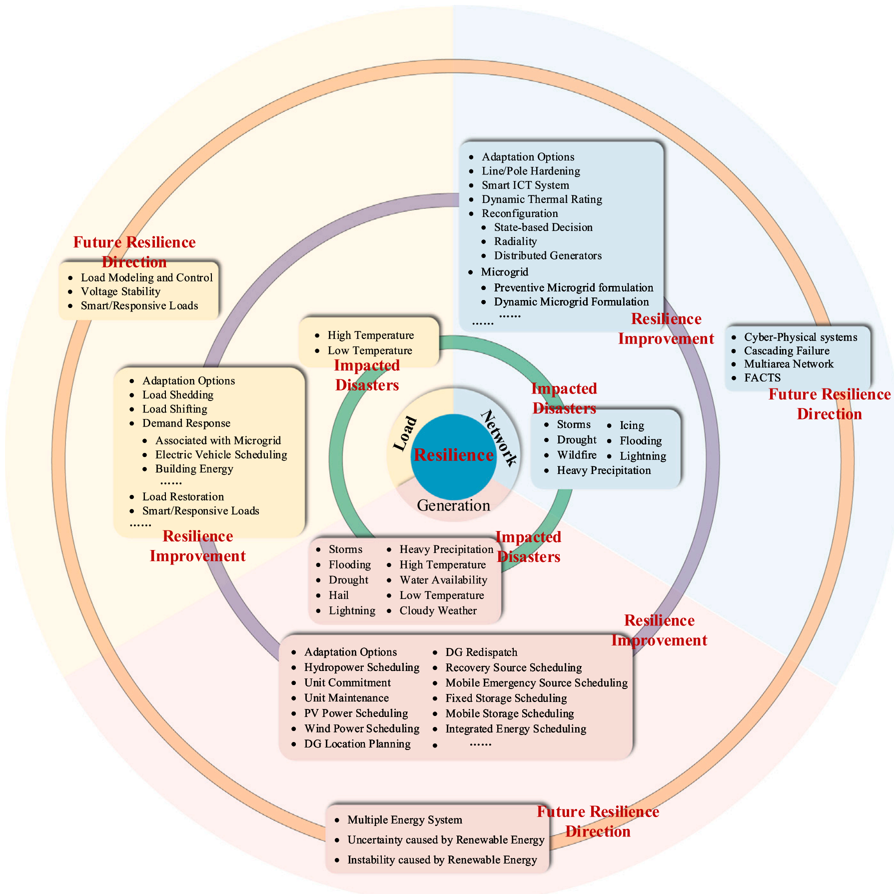

Fig. 1. The graphical abstract of the paper.

system line hardening [8], emergency generator rescheduling [9], active distribution network scheduling [10], microgrid-based scheduling [11], proactive dispatch scheduling [12,13], and event-post restoration [14].

Power systems consist of generators, networks, and loads, which have different characteristics, and these characteristics make them vulnerable to different kinds of extreme weather events or disasters. For example, flooding and warmer air temperatures could have impacts on generators, and could lead to power supply shortage [15]. Wind storms, heatwaves, thunder storms, wildfires, and ice storms could lead to damages on transmission and distribution systems, and result in blackouts and cascading failures. For power loads, heatwaves in summer and extreme cold in winter could cause energy consumption increase and extreme high peak demand, leading to operational risks [16]. Different characteristics require targeted measures and strategies to construct a resilient power system. At present, there are some reviews on power system resilience from the points of cyber–physical systems [17], active distribution systems [18], smart grids [19], microgrids [20], urban energy systems [21]. However, to the best of the authors' knowledge, there are still deficiencies in the systematic review on power system resilience from the perspective of power generation, system networks, and power loads. Therefore, this review is going to bridge the gap, and provide potential research points.

The graphical abstract of the paper is presented in Fig. 1, and the remainder of the review is organized as follows. Section 2 presents power outages due to natural disasters and extreme weather events. Section 3 shows the impacts of extreme weather events on power generation, networks, and loads. Section 4 lists the quantification of the impacts on power generation, networks, and loads. Section 5 shows resilience improvement on power generation, networks, and loads. Innovative directions for future resilience improvements and are discussed in Section 6.

2. Power outages due to extreme weather events and natural disasters

The report released by the Intergovernmental Panel on Climate Change (IPCC) shows that the average global surface temperatures are increasing based on the evidences of more than 750 vital changes in physical variables and more than 28,000 important changes in biological terms [22]. Climate changes play significant roles in the occurrence of extreme weather events, which could cause severe power outages. Table 1 lists worldwide power outages caused by extreme weather events, including ice storms, wind storms, thunderstorms, wildfires, earthquakes, etc. Fig. 2 shows the corresponding statistical results. It is observed that the percentages of outage occurrence caused by wind storms and ice storms are the highest and the second highest, and the corresponding affected people also ranked the second and first places, respectively.

3. Impacts of extreme weather events and natural disasters on power systems

3.1. Impacts on power generation

Currently, many kinds of primary energy can be used to produce electricity, and most of them are impacted by external weather events directly or indirectly. The following sections present the critical weather-related impacts on thermal power, hydro power, wind power, and photovoltaic power, respectively.

Table 1
Power outages caused by extreme weather events or natural disasters.

Date	Country	Extreme event	Affected people
13–17 February 2021	US	Winter Storm	5,000,000
13 February 2021	Japan	Earthquake	809,000
15 August 2020	US	Heat Wave	250,000
26–28 October 2020	US	Ice Storm	400,000
19 July 2019	US	Thunderstorm	277,000
9 June 2019	US	Thunderstorm	350,000
1 December 2019	US	Windstorm	2,000,000
19 July 2019	US	Windstorm	800,000
25 December 2019	Australia	Windstorm	76,000
20 December 2018	Canada	Windstorm	600,000
21 September 2018	Canada	Thunderstorm	172,000
21 March 2018	Azerbaijan	High Temperature	10,000,000
7–10 December 2017	US	Winter Windstorm	900,000
30 October 2017	US	Tropical Storm	1,800,000
26 August 2017	Uruguay	Bad Weather	3,400,000
8 March 2017	US	Winter Windstorm	1,000,000
29 September 2016	Australia	Storm	1,700,000
3 March 2016	Sri Lanka	Thunderstorm	10,000,000
20 September 2015	US	High Temperature	115,000
15 July 2015	US	fire	30,000
23 June 2015	US	Storm	280,000
17 November 2015	US	Storm	180,000
29 August 2015	Canada	Storm	710,000
14 February 2015	US	Cold Front	103,000
27 March 2015	Holland	Windstorm	1,000,000
24 December 2015	US	Wind	105,000
28 November 2015	US	Frosty Storm	110,000
6 March 2013	US	Snow	250,000
22 March 2013	Northern Ireland	Snow Storm	200,000
22 March 2013	UK	Snow	211,300
15 March 2013	Hungary	Snow	100,000
27 February 2013	US	Snow	50,000
11 February 2013	US	Snow	113,000
30 January 2013	US	Storm	60,000
2 January 2013	Canada	Wind	100,000
13 March 2013	Australia	Heat Wave	1,500
12 December 2013	Canada	Storm	500,000
December 2013	France	Wind	240,000
29 June 2012	US	Thunderstorms	3,800,000
29 October 2012	US	Hurricane	8,100,000
22 February 2011	New Zealand	Earthquake	160,000
14 March 2010	Chile	Earthquake	15,000,000
25 July 2010	US	Windstorm	250,000
20 July 2009	UK	Fire	100,000
10–20 December 2009	Brazil, Paraguay	Thunder Storm	80,000,000
27 January 2009	US	Ice	769,000
23 January 2009	France	Windstorm	1,200,000
January–March 2007	Australian	Fire	200,000
8–12 December	US	Ice	1,500,000
2 December 2007	Canada	Winter Storm	100,000
2 August 2006	Canada	Thunderstorms	250,000
1 August 2006	Canada	thunderstorms	450,000
22 July 2003	US	Storm	300,000
30 January 2002	US	Ice	270,000
26–28 December 1999	France	Cyclone	3,400,000
January 1998	North America	Ice	3,500,000
7 July 1991	US	Storm	1,000,000
13 March 1989	Canada	Storm	7,000,000
31 May 1988	North America	Storm	2,000,000
17 May 1985	US	Fire	4,500,000
13 July 1977	US	Lightning Strike	9,000,000
February 2008	China	Ice	25,000,000
16 September 2014	China	Typhoon	4,000,000

3.1.1. Thermal power

3.1.1.1. Impacts caused by heavy precipitation and flooding. At present, thermal power is still important. It is estimated that about 70% of total electricity is from thermal power by 2030 and coal accounts for about 38% [23]. Too much water such as heavy precipitation and flooding could increase moisture content into coal and lead to quality degradation of coal stockpiles. In addition, heavy precipitation and flooding could have negative impacts on transportation, which may delay the coal delivery. For example, coal mines were closed in Australia in early 2011 because of heavy precipitation and flooding caused by La Nina weather.

In addition to power reduction due to primary sources caused by heavy precipitation and flooding, some thermal power plants directly located at low-lying areas are vulnerable to flooding directly. This could result in severe power outages. In January 2013, a serious flood, in the Northern coast of Jakarta, resulted in shut down of a 909-megawatt power plant for twelve days [24]. From April 2011 to December 2013, more than 280 power plants and energy facilities in U.S. were affected by flooding and sea level rise [25].

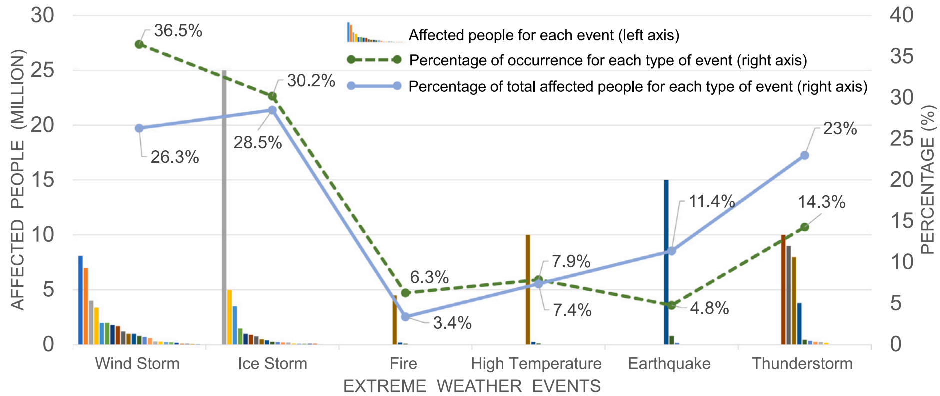

Fig. 2. Statistical results for power outages due to extreme weather events or natural disasters.

3.1.1.2. Impacts caused by high temperature. A raise in external temperature leads to a decrease in the temperature difference between combustion and ambient, and in consequence the decreased temperature difference will reduce the efficiency of turbines, boilers and gensets, respectively. The gas-fired units have higher efficiency reductions in power generation compared to coal-fired units. It is estimated that appropriate 3% to 4% of power generation will be reduced due to an increase of 5.5 ℃ in external temperatures [26].

In addition, high temperatures will cause higher water temperatures. If a power plant has incoming water with high temperatures, the plant's efficiency will be reduced. If a power plant has discharge water with high temperatures, which is out of compliance with government temperature regulations with regard to local ecosystem protection, power plants need to shut down temporarily. For example, extreme high temperatures in North Caroline resulted in high temperatures of water for cooling Allen coal plants in 2007, and this caused power generation reduction and blackouts in nearby areas.

3.1.1.3. Impacts caused by drought and water availability. Thermoelectric generation heavily depends on water supply, and water is employed as cooling purposes. For a plant with once-through cooling systems, it needs 10,000–60,000 gallons water for cooling systems when producing per MWh electricity. For a plant with recirculating systems, it just needs 250–1800 gallons water for cooling systems when producing per MWh electricity [27]. Severe drought could make water levels drop below the available water level for cooling systems, and in consequence could result in generation reduction or power outages. A report based on more than 420 thermoelectric power plants demonstrated that about 43% of these plants once had the situations that cooling-water intake heights are lower than the typical water level. In 2012, drought caused a low water level in Iowa's Cedar River in U.S., and the system operators in a nearby plant had to dredge the river to satisfy water availability [28].

3.1.2. Hydro power

3.1.2.1. Impacts caused by drought and high temperature. Hydro power heavily depends on water to produce electricity. Drought usually leads to less available water, and in consequence results in less hydroelectricity. For example, drought from 2007 to 2009 caused a decrease in electricity from hydro power to 13% of overall electricity generation in California compared to an annual average of 18%. From 2011 to 2015, electricity from hydro power is much lower, at about 10.5% of the total electricity generation, due to the drought. As the world's second largest producer of hydro power, Brazil faces challenges caused by drought in recent years. In 2013, hydropower decreased by 7% in Brazil, and an additional 5.5% in 2014. The biggest dam in Brazil was only at 16.1% of its capacity in December 2014. Usually, power generation has a complicated relationship with regard to runoffs, temperatures, water declines, etc. However, some generic relationships for specified hydro plants can be described. For example, 5–6 MW of power for Hoover Dam in U.S. could be reduced when having each foot decline in Lake Mead [29]. For Colorado River Basin, 3% of hydro power will be reduced when streamflow has 1% decrease [29]. Hydrologic patterns, which have great impacts on river runoffs, depend on ambient temperatures. High temperatures cause the acceleration of glaciers melting in Northern Hemisphere in earlier spring, and in consequence changes river runoffs and impacts hydro power. In addition, high ambient temperature could result in more evaporation, which would reduce electricity generation from hydro power. The rate of evaporation depends on the water surface area. A larger surface area makes a reservoir more vulnerable to evaporation.

3.1.2.2. Impacts caused by heavy precipitation and flooding. In contrast of drought, heavy precipitation contributes to increase river flows and leads to high water levels of reservoirs, and in consequence makes a positive impact on the capability of generating much more electricity. However, excessive water inflow caused by heavy precipitation could result in water spills of reservoirs, and furthermore increases the downstream flow that could cause flooding potentially. From March to April of 2010, heavy precipitation along the Citarum caused a large amount of water inflow into the Saguling reservoir and the Cirata reservoir, resulting in downstream flooding [30]. Based on historical data, it shows excessive water inflow is followed by water spillage, and Saguling hydroelectric power plants have the highest record of water spillage over 29 years in 2016 [24]. In addition, debris loads and large sediments carried by flooding could block dam spillways, and in consequence the powerful masses of water could have a severe damage on significant structural components [31].

3.1.3. Wind power

3.1.3.1. Impacts caused by low temperatures. Different materials employed for wind turbine fabrication can be adversely affected by low temperatures. For example, steel becomes more brittle as a lower temperature, and in consequence the energy absorbing capacity would be reduced. When having a low temperature, the components, e.g., dampers, hydraulic couplers and Gearboxes, are exposed to cold weather. The viscosity of the hydraulic fluids and the lubricants would be adversely impacted, and in this case gears could be damaged due to thick oil. Furthermore, the power transfer capacity of the gearbox will also decrease due to oil viscosity with unacceptable level. Low temperatures could also make cushions and seals loose flexibility, and in consequence lead to a general decline in performance [32].

3.1.3.2. Impacts caused by icing. When the temperature is extreme low, wind turbines usually suffer from icing, which is one of the most critical threats to wind turbines in cold winter. It is expected that wind turbines have the capabilities of sustaining limited icing without damages. Usually, there are two kinds of icing, i.e., glaze and rime. The wind turbine blades are most vulnerable to the negative influences caused by icing and many operational problems such as turbine performance, ice shedding/throw, and electricity generation reduction. A project in Finland and Sweden demonstrated that freezing conditions led to between 9% and 45% of downtimes for wind turbines [33].

3.1.3.3. Impacts caused by high-speed wind storm. Wind speed is critical to wind turbines for power generation, but extreme high-speed wind could have great negative impacts on wind turbines. Extreme wind speeds, caused by typhoons, hurricanes and tornadoes, might exceed the maximum operational conditions for designed wind turbines, and could result in shut-down of wind turbines or wind power generation reduction. In 2003, typhoon Maemi, of which the maximum wind speed reached to 60 m/s (equivalent to a Category 4 hurricane), caused seven wind turbines in Japan in failure [34]. In 2017, hurricane Maria (a Category 4 hurricane) had severe impacts on two wind farms in Puerto Rico [35]. In China, several wind turbines were damaged by typhoon Dujuan [36].

3.1.4. Photovoltaic and solar thermal power

3.1.4.1. Impacts caused by high temperature. Usually, the efficiency of a solar photovoltaic module will decrease as ambient air temperatures increase. For example, some studies [37] show that the efficiency rated at 25 °C will decrease by about 0.25% to 0.5% per 1 °C increase. Crystalline Si modules and current thinfilm are also negatively impacted by high temperatures. In addition, heat waves caused by high temperatures also have negative effects on panel aging, and some materials cannot be capable of withstanding extreme high temperatures. Solar thermal power usually depends on dry cooling, of which the efficiency is impacted by ambient temperatures. Existing studies show that the efficiency will drop by 3% to 9% as the ambient temperatures increase from 30°C to 50°C. The efficiency could drop by up to 18% in one hour. [38].

3.1.4.2. Impacts caused by cloudy weather, hail, lightning. As the sun is blocked by clouds, the relative fraction of diffuse light will increase, and in consequence the photovoltaic panel is at a disadvantage to concentrate diffuse light with generation reduction. For the solar thermal power stations, the diffusion caused by clouds reduces the capability of the mirrors to concentrate sunlight and reduce the power generation.

For photovoltaic power and solar thermal power, their major physical components are directly exposed to external environment. Fracture of glass plates of photovoltaic modules and mirrors in solar thermal power stations could be caused by hailstorms, and will directly or indirectly lead to damages on photovoltaic modules and mirrors.

The international standard IEC 61215 demonstrates that panels should have the capacity to withstand the impacts caused by 25 mm hailstones at 23 m/s. Furthermore, the inverter is one of most unreliable components in a photovoltaic system. Studies show that the inverters account for over 60% of unscheduled maintenance costs [39].

3.1.4.3. Impacts caused by wind and sand. One of important negative impacts caused by wind is dust and sand deposition, which could lead to photovoltaic power reduction. One study on a thin-film system shows that the humidity would have a negative impact on dust accumulation. For solar thermal power stations, the mirrors can be turned upside down to be protected from storms with sand, however, it is necessary to clean the mirrors carefully and this process might take several days with power reduction [40]. In addition, the mirrors in the solar thermal power stations also suffer from daily accumulation of dust, which could reduce the station efficiency.

3.2. Impacts on networks

3.2.1. Impacts caused by storm with heavy precipitation, flooding and lightning

A warmer atmosphere results in more storms, hurricanes, and typhoons that increase the risks of lightning, high-speed wind, heavy precipitation, and surface flooding. All of these events could have direct or indirect impacts on power networks. The most apparent influences caused by high-speed winds on the system networks are wind load pressures, which could result in severe damages on overhead power lines, transformer stations, towers and pylons. For example, Hurricane Sandy in October 2012 caused havoc on transmission and distribution systems. It was reported that more than 7000 transformers and 15,200 poles were damaged [2]. During the extreme event, over 10% of its large distribution substations and over 35% of its transmission substations in New York City were at risk due to flooding. In Switzerland, Southern Germany, and Northern France, over 200 pylons were destroyed by the storms "Lothar" and "Martin" with extreme high-speed winds in 1999 [41]. Between 2014 and 2015, more than 360 recorded floods affected distribution networks in Java and Bali in Indonesia. Table 2 lists some network-related damages caused by storms.

Table 2
Damages to networks due to storms.

Storms	Areas	Damages
Kyrill (Jan 2007)	Poland, Austria	Network Damages
Klaus (Jan 2009)	France	Loss of Electricity Pylons
Anatol (Dec 1999)	Denmark, Scotland	Network Damages
Thorsten (Nov 2005)	Germany	Bending of Network Masts
Xynthia (Feb 2010)	Denmark	Network Damages
Franz (Jan 2007)	Germany	Overhead Line Damages
Annette (Feb 2008)	Northern Germany	Bending of Network Towers
Emma (Mar 2008)	Southern Sweden	Transformer Damages

The lightning strike is also one of major causes of power outages in the networks even though the networks are equipped with insulation and shield wire used to protect from lightning strikes. Lightning strike could cause direct damages to devices due to an increase in charge transfer, rate of current rise, and peak current, respectively. In addition, indirect damages, due to creeping currents, electromagnetic pulses, and overvoltage, could be also caused. From 2011 to 2017, there were over 100 transmission network-related outages in Java and Bali due to lightning strikes [24].

3.2.2. Impacts caused by drought and wildfire

Drought is one of important causes of wildfires, which threat the system networks. First, transmission and distribution lines could be burned down, and transmission poles could be damaged due to nearby fires. Second, line conductors could be damaged or annealed, and subsequently in failure. Third, the ambient air could be ionized by ash and smoke from fires, creating an electrical path away from lines, and this could lead to power outages. For example, two high-voltage transmission lines in New Mexico in 2011 were at high risk due to the Las Conchas wildfire, and affected more than 400,000 customers. Wildfires in California in 2007 caused the Southwest Powerlink transmission system in failure, and 500 MW of electric loads were reduced [42].

3.2.3. Impacts caused by icing

System networks can be affected by icing in three ways. The first one is that the electrical strength of the insulator could be reduced due to ice accumulations and in consequence icing flashover is caused. The second one is that air gaps between heavy ice conductors and ground wires are reduced and sleet jumping could be caused when ice starts to melt on the conductors. The third one is that topple towers and the conductors could be damaged due to icing. Many regions, e.g., North America, Europe, Nordic region, Asia and South Africa, suffer from severe damages to power system networks due to icing disasters. For example, there was a heavy snow in the coastal area called Costa Brava in 2020. However, the transmission towers were not designed to withstand the unexpected extra icing load, and the network was destroyed. In 2008, the southern parts of China suffered from severe incing events, which caused more than 8000 electrical towers collapsed [43].

3.3. Impacts on end-user load

Usually, electricity demand is heavily influenced by temperatures. Cooling demands and heating demands account for about half of residential energy use and a third of commercial energy use. It is investigated that a temperature increase of 1℃ will cause 3%–7% increase in demands [44]. When the temperature rises from 24℃ to 30℃, the average electricity demands in India increase by about 10%, and the aggregate demands in Delhi increase by 30%. Extreme weather will increase the risk of excessive peak demands. For example, an extremely high temperature was caused by a heat wave from the Midwest to the Atlantic coast in U.S. from July 15–22, 2019, and the recorded demand peak was 704 gigawatts (GW) based on data from the U.S. Energy Information Administration's. In March 2008, heat waves affected the South Australian region, in which unexpected excess burden was caused by air conditioning [45]. In addition, severe low temperatures could also result in extreme high load peak. One recent example is Texas power outage in February 2021. During this period, 50° F below average in Texas due to a rare polar vortex caused an extreme high load peak (more than 69 GW).

4. Quantification of impacts on generation, network, and load

Different sectors of power systems may be affected by various weather events, and the corresponding characteristics are also different. The sectors in the power systems may have lower efficiency or be in failure with probabilities. The following sections list the quantification of the impacts of weather events on generators, networks, and loads. The corresponding quantification is listed in Table 3, Table 4, and Table 5, respectively.

5. Resilience improvement

5.1. Generation perspective

To make generation more resilient against extreme weather events, some adaptation options for specific components could be implemented. In addition, generation operation and optimization could also improve generation resilience against extreme weather events. Therefore, resilience improvement will be introduced from these two perspectives.

5.1.1. Adaptation options for generation

The possible adaptation options are listed in Table 6, and the critical factors with great impacts would be presented. For example, thermal power is more vulnerable to heavy precipitation, flood, less precipitation, drought, and high temperature. The adaptation options are mainly implemented to deal with these factors.

5.1.2. Generation operation and optimization

Many studies focus on system resilience from the perspective of generation operation and optimization, as shown in Fig. 3.

5.1.2.1. Conventional generation. Hydropower is one of important conventional generation, which is directly determined by water availability, and hydropower produces more than 16% of worldwide electricity. Unexpected extreme weather-related events could have adverse impacts on hydropower scheduling [82]. For example, the higher streamflow variabilities caused by extreme weather events lead to decline in hydropower production although the overall streamflow is increased [83]. It is necessary to investigate hydropower resilience against weather-related events [84]. To help system operators manage hydropower generation with more resilience against climate changes, the impacts of climate changes on hydropower outputs, efficiencies, sustainability, and reservoir inflows are evaluated in [85]. In [86], the climate changes' impacts on the performance of the Three Gorges Reservoir from the long-term perspective are analyzed by investigating the hydropower models and the daily reservoir regulations. The results show that the performances of reservoirs are highly sensitive to unexpected severe streamflow. An increase of streamflow in the flood seasons usually lead to a significant increase of spilled water. In [87], the performances of hydropower production in consideration of climate changes' impacts on river discharge are compared to the scenarios without consideration of climate changes' impacts. Applying climate-change-driven optimal strategies for reservoir management could have great positive influences on hydropower production, and could mitigate the negative influences caused by climate changes. In [88], a long-term model for water system management and electricity supply is constructed to investigate the hydropower expansion plans against potential climate changes. In [89], precipitation forecasts are investigated to help system operators make resilient optimal strategies in consideration of varying precipitation.

To improve the generation resilience, appropriate scheduling of conventional generators could be implemented to redistribute power flow so that the system could have higher reliability against potential extreme weather events. Appropriate maintenance scheduling of generators can improve the component reliability against potential extreme weather events [90]. Resilience-constrained unit commitment models are proposed in [91] and [92], in which the system operational constraints and the component failure rates due to extreme weather events are included. In [93], a two-stage robust optimization model for resilient unit commitment, in consideration of day-ahead operational constraints, is investigated. The uncertainties caused by extreme weather events are represented as a group of distributed chance constraints. In [94], a stochastic unit commitment model, in which uncertain system outages caused by natural hazards are explicitly expressed, is investigated. The efficiencies of thermal units are impacted by high temperatures, and [95] investigates the impacts of high temperatures on generator outputs. The proposed model has the capability of capturing the potential impacts of heat waves on production costs and system reserves. In [12], system states caused by extreme weather events are expressed as Markov states, and a recursive unit commitment model for a state-based decision-making process is proposed to obtain resilient sequential strategies. The above papers mainly focus on scheduling from the steady-state perspectives. However, dynamic responses after failures, e.g., generator failure or line failure, could also have severe impacts on system operation, and need more investigations when scheduling generation.

5.1.2.2. Renewable energy. Renewable energy, typically photovoltaic power and wind power, will have higher percentages in total power generation. With the increasing percentages of wind power and photovoltaic power, the impacts of extreme weather events on them would be critical to improve the entire system resilience. For example, photovoltaic power could be a means to supply local loads when the main networks are in outages due to hurricanes. However, hurricanes indicate severe cloud cover, which directly reduces the photovoltaic power outputs. Investigations show that the photovoltaic power outputs during hurricanes range between 18% to 60% under the normal weather conditions [96]. In [69], system resilience with regard to different percentages of wind power and photovoltaic power under potential hurricanes is investigated. In [97], the networked microgrid with roof-top solar is employed to improve the distribution system resilience in the face of extreme natural disasters. Photovoltaic power scheduling and wind power scheduling in consideration of uncertain conditions caused by natural disasters are investigated to improve the distribution system resilience in [98] and [99], respectively. In practice, some critical buses with appropriate power sources could have great contributes to improve power system resilience. In [100], the metric of capacity accessibility is developed to identify critical buses, and a resilience-oriented model for scheduling the size and the location for photovoltaic power at critical buses is investigated. In [101], a

Table 3
Quantification of the impacts on generators.

Events	Components	Quantification	References
Earthquake	Power Plant	The failure probability can be expressed as a failure curve with regard to the peak ground acceleration (PGA) of the earthquake, and PGA can be expressed as follows. $\log_{10}(PGA) = -1.55 + 0.26M + 0.01h - 0.01R - (1.52 - 0.10M)\log_{10} R$ where M is the magnitude of the earthquake in the Gutenberg–Richter scale, r and R are the parameters with regard to the location and earthquake's magnitude.	[46]
High Temperature and Heat Waves	Power Plant	For the thermal plant with closed-loop cooling system, a piece-wise linear function is employed to express the impact of ambient temperature on available capacity C_t. $C_t = \begin{cases} 1 & T_t \leq T_h \\ 1 - \rho(T_t - T_h) & T_t > T_h \end{cases}$ where T_t is the ambient temperature, T_h is the temperature threshold, at which the power plant can run at their normal operating efficiency, ρ is the efficiency degrading rate.	[47]
	General Electric Combined-Cycle Unit	A curve of the maximum capacity with regard to the ambient temperature is presented. The maximum capacity is about 83% of the rated capacity when the ambient temperature is 37.8℃ .	[48]
	Power Plant	The quantitative vulnerability for a generating unit with regard to the heat wave is represented as $Q_G = T_G \times T_G \times C_G$.	[49]
	Natural Gas Combined Cycle	Temperature-response curves show that 1℃ increase will lead to a decrease of about 0.5% in the plant capacity.	[50]
	Gas Turbine	0.1% thermal efficiency will decrease with per ℃ increase.	[51]
	Power Plant	A decrease of 0.12% in the thermal efficiency will be caused by per ℃ increase in cooling water temperature.	[52]
	Nuclear Plant	Empirical data show that per ℃ decrease in the ambient temperature between -7℃ and 20℃ would cause about 0.4% output reduction, and about 1% output reduction would be caused when the ambient temperature is higher than 20℃ .	[53]
	Photovoltaic	The temperature-response function with regard to the electrical efficiency can be expressed as follows. $\eta_c = \eta_{ref}(1 - \beta(T_c - T_{ref}))$ where η_{ref} is the electrical efficiency at the reference temperature T_{ref} and solar radiation, β is a parameter, T_c is the cell temperature.	[54]
Wind	Wind Turbine Tower	The probability that a turbine tower is buckled can be expressed as follows. $p_{wt} = \frac{(v/\alpha)^\beta}{1+(v/\alpha)^\beta}$ where v is the wind speed, α is the scale parameter, and β is the shape parameter.	[55]
	Wind Turbine Tower	Inelastic response plays an important role in tower collapse, and the stress concentration factor (SCF) is investigated to calculate the local stress of the failure section. $\text{SCF} = 1 + \frac{6(\delta_t + \delta_m)}{t} \frac{1}{1+(T/t)^\beta} e^{-\alpha}$ where δ_t is the shift in the neutral axis, δ_m is the fabrication tolerance, α and β are the parameters related to the turbine tower. T and t are the thicknesses of the thicker and thinner steel shell.	[56]
Flood	Power Plant	The Fragility curve is estimated by using a lognormal distribution as follows. $Mean = a \cdot e^{B/2}$ $\text{StandardDeviation} = Mean \cdot \sqrt{e^{B_c^2} - 1}$ where a, B, and B_c are the parameters with regard to flood.	[57]
	Power Plant	Given fragility curves with regard to flood are presented.	[58]
	Power Plant	A damage function with regard to the flood magnitude x and the magnitude threshold λ is expressed as follows. $d = g(x - \lambda)$ where d denotes the damage, and g denotes the damage function, which has the lowest value of 0 when $x < \lambda$ and increases monotonically to its maximum values when $x \geq \lambda$.	[59]

two-stage stochastic optimization model for wind power allocation is investigated to improve the distribution system resilience against natural disasters. Results prove the importance of wind power allocation with regard to resilience improvement. In addition, wind power and photovoltaic power can accelerate the restoration process and improve the system resilience [102]. However, high penetration of wind power and photovoltaic power could cause more uncertainties into the power systems, potentially resulting in instability issues in the face of extreme weather events or natural disasters. One of critical points is to predict renewable energy, and artificial intelligence methods, e.g., artificial neural networks [103], general regression neural networks [104], and deep learning neural networks [105], are effective methods to predict renewable energy.

5.1.2.3. Distributed generators. Locations and sizes of distributed generators could have great impacts on system resilience improvement. Two-stage models can be used to deal with this issue. In [106], distributed generation resource allocation associated with network planning is

Table 4
Quantification of the impacts on networks.

Events	Components	Quantification	References
Earthquake	Distribution Lines	Damage functions are expressed as the lognormal fragility curves. The probability p with regard to damage is described as follows. $p=\Phi\left[\frac{1}{\beta}\ln\left(\frac{S_d}{S_{d,s}}\right)\right]$ where $S_{d,s}$ is the median value, S_d is the spectral displacement, β is the parameter related to the earthquake, and Φ is the standard cumulative normal distribution function.	[60]
Wildfire	Power Lines	The effective rating of the conductor could be reduced by 40% due to a wildfire in the range of 20–30 meters.	[61]
	Power Lines	The change in conductor temperature ΔT is expressed as follows. $\Delta T=\frac{\Delta t}{C_p}(q_l+q_s+q_f-q_c-q_r)$ where Δt is the time interval, q_l is the ohmic loss, q_s is the solar radiation, q_f is the radiative heat flux, q_r is the radiative heat loss, q_c is the convective heat loss. The conductor temperature determines the line capacity.	[62]
Flood	Substation	A flood vulnerability level, which is related to maximum water depth, is assigned to each substation, and different locations have different maximum water depths.	[63]
	Substation	Given fragility curves for three types of substations, and the curves are functions of flood depth.	[58]
	Underground wires	The failure probability p can be expressed as follows. $p=[a+b\cdot(H-S)]\cdot F_{HS}$ $F_{HS}=\begin{cases}1 & H-S\geq 0\\ 0 & H-S<0\end{cases}$ where H is the hurricane category	[64]
Wind	Power Lines	The failure rate p can be expressed as follows. $p=\lambda\left[1+k\left(\frac{v^2}{v_T^2}-1\right)\right]$ where λ is the failure rate under the normal conditions, k is the parameter, v is the wind speed, v_T is the threshold value of the wind speed.	[65]
	Power Lines	The line failure rate p is expressed as a lognormal cumulative distribution function as follows. $p=\Phi\left[\frac{1}{\kappa}\ln\left(\frac{v}{M}\right)\right]$ where v is the wind speed, Φ is the lognormal cumulative distribution function, κ is the logarithmic standard deviation, and M is the median of fragility function.	[66]
	Arcing Poles	The damage extent (DE) is expressed as follows. $DE=\frac{w_f\cdot h_f}{a\cdot w_p^2}$ where a is the height/width ratio with regard to poles, w_p is the width of the pole bounding box, h_f and w_f are height and width of the damage bounding box.	[67]
	Substation	The failure probability p with the given wind speed can be expressed as follows. $p=\Phi\left[\frac{\ln(v)-u}{\sigma}\right]$ where u and σ are the logarithmic mean and the standard deviation, and v is the wind speed.	[68,69]
	Power Lines	The failure rate of the line between two adjacent towers can be expressed as follows. $p=\Delta l\cdot\exp\left(\frac{11\cdot v}{v_d}-18\right)$ where Δl is the length of the line, v is the wind speed, v_d is the design wind speed for the line.	[70]
	Tower	The time-varying failure probability p for the tower can be expressed as follows. $p=\int_{-\inf}^{K_T}\frac{1}{\sigma_T\sqrt{2\pi}}e^{-(x-u_T)^2 2\sigma_T^2}dx$ where K_T is the equivalent wind speed rate at the tower, u_T and σ_T are design parameters for the tower.	[71,72]
	Poles and Conductors	The fragility curves can be used to estimate the failure probability p that is expressed as follows. $p=a\cdot e^{b\cdot v}$ where v is the wind speed, and a and b are the parameters with regard to poles and conductors.	[73,74]
Ice	Power Lines	The line probability p caused by ice can be expressed as follows. $p=\begin{cases}0 & L_w\leq a_w\\ \exp\left[\frac{0.6931(L_w-a_w)}{b_w-a_w}\right]-1 & a_w<L_w\leq b_w\\ 1 & L_w>b_w\end{cases}$ where a_w and b_w are the first threshold value and the second threshold value with regard to lines, respectively, and L_w is the ice–wind load.	[75]
	Power Lines	The failure probability is expressed as the fragility curve with regard to the ice thickness, which is represent as follows. $R_{it}=\frac{H}{\rho_i\pi}\sqrt{(P\cdot\rho_w)^2+(3.6\cdot V\cdot L)^2}$ where R_{it} is the ice thickness, V is the wind speed, L is the liquid water content, P is the precipitation rate, H is the freezing hour, ρ_i and ρ_w are the density of ice and water, respectively.	[76]

Table 5
Quantification of the impacts on loads.

Events	Components	Quantification	References
Temperature	Electricity Demand	Temperature response function is used to reflect electricity demand with regard to temperature changes. Different regions have different parameters for the temperature response function.	[77]
	Electricity Demand	Electricity demand curves of cooling and heating with regard to the temperature are investigated.	[78]
	Electricity Demand	The percentage of the electricity demand increase caused by the temperature increase is expressed as follows. $D_p = (5.33 - 0.067 \cdot L) \cdot \Delta T$ where D_p is the percentage of the electricity demand increase, L is the latitude in decimal degrees, and ΔT is the temperature change.	[79]
	Electricity Demand	Demand D for cooling is expressed as a function with regard to cooling degree days (CDD) as follows. $D = k \cdot (CDD \cdot \alpha + IG) \cdot (1 - \exp(\beta))$ where k is the unitless calibration coefficient, α is the parameter with regard to the average surface-to-floor area ratio and thermal conductance, IG is the internal gain caused by heat from equipment in buildings, and β is a parameter related to cooling technology and per capita income.	[80]
General events	Electricity Demand	Statistics-based formulas for resilience metrics such as restore duration, customer hours not served, and restore rates, are established.	[81]

established as a two-stage robust optimization model with the minimum system damage as the objective, and an uncertainty set is used to represent the uncertain temporal and spatial impacts caused by natural disasters. In [107], a two-stage stochastic planning model, in consideration of emergency conditions caused by a weather-related event and its duration, is established to allocate distributed generators. In [106], a two-stage stochastic model, where the first stage determines the location and the size of distributed generators and the second stage determines the post-event restoration, is proposed to improve the system resilience. In [62], distributed micro-turbines are scheduled by means of a stochastic programming approach to increase the capability of dealing with an approaching wildfire. In [108], negative effects, caused by extreme weather events, are minimized by scheduling distributed generators. In [109] and [110], resilience-oriented optimal strategies for distributed energy resources are investigated to minimize load shedding. During power outages after extreme weather events, system operators expect to implement system recovery as quickly as possible. Distributed generators can be used to accelerate the recovery process. In [111], a resilient restoration strategy with distributed energy resources is proposed to minimize the recovery time and maximum the restored critical loads. A decision-making recovery process in consideration of multiple distributed sources is investigated in [112] to supply critical loads after weather-related outages. In addition to common operational constraints, some constraints, e.g., inrush currents and circulating currents among distributed generators, are also considered to make the resilience-oriented recovery strategies more practical [113]. In [114], distributed generators are scheduled as black-start resources for bulk systems after blackouts. The above papers mainly investigate optimal scheduling on fixed distributed generators, however, mobile emergency generators also play important roles in power system resilience enhancement. Usually, the problem can be described as a two-stage model, in which the first stage is to determine the pre-allocation of mobile emergency generators before a weather-related event and the second stage is to dynamically dispatch mobile emergency generators to assist system recovery [115]. In addition, some other types of mobile sources such as mobile marine power sources [116] and mobile de-icing sources [117] can be also used to improve the system resilience. When dispatching mobile emergency generators, transportation and crew availability is also important. In [118], a co-optimization model, in consideration of different timescales of crew dispatch and distribution system restoration, is established to schedule mobile emergency generators in consideration of transportation constraints.

5.1.2.4. Energy storage. Energy storage is also an important means to increase system resilience against different natural disasters [119,120]. One important function of energy storage is to balance power supply and demand during disturbances [121,122]. In addition, energy storage can enable repair to be performed without resorting to global recovery, and keep the unwanted blackout effects to minimum. To enhance system resilience, one critical point is to determine locations and sizes for fixed storage. In [60], a resilience-driven optimization model is investigated to determine the location and the capability of battery energy storages against potential earthquakes. Storages with appropriate locations and sizes can work as generation sources to accelerate the restoration process [100]. Resilience-oriented models for scheduling storages are investigated to deal with hurricanes [123], and

Table 6
Adaptation options for generation.

Components	Events	Adaptation options	Effects
Thermal Power	Heavy Precipitation, Storm, flood	• Coal stockpile and fuel storage protection • Flood control improvement (higher channel capacities, flood defense barriers, dikes) • Coastal defenses (bulkheads and seawalls) • Exposed place protection, fuel storage protection • Reroute water pipes	• Improve coal quality and increase combustion efficiencies • Reduce coastal infrastructure damages caused by increased sea levels
	Less Precipitation, Drought	• Cooling system improvement (wastewater usage, evaporative loss reduction, dry cooling tower improvement) • Develop new water sources, and increase volume of water treatment works • Water intake pipes improvement	• Increase availability of freshwater for cooling in consideration of less water
	High Temperature	• Decentralize generation • Locate power plants in regions with lower temperatures • Improve cooling systems to increase pumping capacities • Construct a "helper" cooling tower	• Increase the efficiencies of power plants. • Reduce the temperature of discharged cooling water
Hydropower	Precipitation Increase	• Modify tunnels or canals to deal with changes in water flows • Change types of turbines that are more suitable to water flows • Build cascade hydropower stations	• Reduce the uncertain impacts of precipitation changes on hydropower outputs
	Precipitation Decrease, Drought	• Install controllable spillway gates, and modify spillway capacities • Augment water storage reservoirs • Reservoir management	• Reduce the risk of damages from silt
	High Temperature, and wind speed	• Augment water storage reservoirs	• Reduce surface evaporation
Wind Power	Icing	• Heating wires, and inflatable membranes along the blades • A cover of nanostructured materials	• Icing protection
	Lightning Storm	• Lightning rods at the nacelle • Lightning protection in the blades • Galvanic separation, overvoltage arresters	• Protect against damages from lightning
	Storm Surges	• Stronger structures of towers and foundation	• Protect against structure damages
Photovoltaic Power	Greater Cloud Cover	• Distributed access to networks • Locate photovoltaic cells in regions where the cloud cover is low	• Increase photovoltaic efficiencies/outputs
	High Wind, Storm Surges	• Use more robust cell structures and stronger mounting structures • Reinforce cabling and components	• Prevent against structure damages
	Higher temperatures	• Improve airflow beneath mounting structures • Structure/cell improvement for high temperature peaks	• Increase energy outputs and cell efficiencies

wildfires [62], respectively. To better utilize fixed storages, microgrids and network reconfiguration can be used together to obtain optimal resilient strategies [98].

In addition to the fixed storages, mobile energy storages can be also scheduled by means of optimizing locations before natural disasters and re-routeing after natural disasters to enhance system resilience [124]. To include uncertainties caused by transportation networks and renewable energy sources, stochastic models in consideration of temporal–spatial constraints are constructed to schedule mobile energy storages and improve distribution system resilience [125]. Similar to the fixed storages, mobile energy storages can be also dispatched with microgrids and network reconfiguration to further improve the system resilience [126].

5.1.2.5. Integrated energy. The coupled integrated energy systems provide alternative operation modes for power systems in the face of unpredictable failures caused by natural disasters [127]. Currently, investigations on energy resilience, e.g., evaluation indicators and resilience enhancement, are still in their infancy. Operational metrics and infrastructure metrics in consideration of the spatial and temporal

Fig. 3. Generation operation and optimization for system resilience improvement.

impacts of hurricanes on the interdependent power and natural gas systems are employed to quantify the system resilience [128,129]. To ensure have a resilient energy supply from long-term perspectives, system planning should be coordinated. To optimize planning strategies, the impacts caused by natural disasters and the system operational constraints need to be included. In [130], a two-stage robust planning model, in which the interactions between extreme events and energy systems are described as a variable uncertainty set, is established to improve energy system resilience against extreme conditions. In [131], a two-stage planning model, in consideration of resilient operation strategies for emergency sources, is investigated to better adapt to severe conditions. Furthermore, some preventive and proactive strategies, by means of dispatching power generators and gas sources, are investigated to improve energy system resilience [132]. Compared to power systems, underground natural gas networks, which are less vulnerable to extreme weather events, contribute to accelerate repair processes by means of collaborative restoration models. However, electromagnetic and electromechanical dynamics of power systems usually have fast responses than other energy systems, e.g., natural gas systems. The responses with different time-scales have great impacts on system operation against natural disasters, and more investigations need to be focused on (see Table 7).

5.2. Network perspective

Similar to generation, some adaptation options with regard to specific network components, e.g., lines, poles, and substations, can be implemented to make networks more resilient. Furthermore, some additional ways, e.g., system hardening, system reconfiguration, and microgrid formulation, can be employed to improve system resilience from the perspective of networks.

5.2.1. Adaptation options for network

The possible adaptation options are listed in Table 8, and the table lists the main factors.

5.2.2. Network operation and optimization

There have been many studies on system resilience from the perspective of network operation and optimization, as shown in Fig. 4, including line/pole hardening, microgrid formulation, system reconfiguration, etc.

5.2.2.1. Network hardening. For transmission and distribution systems, many of their components are directly exposed to extreme weather events and natural disasters. One effective means to improve network resilience is component hardening, e.g., pole/line hardening. For example, the U.S. National Electric Safety Code requires that poles should be replaced when the remaining strength is below two-thirds of the initial strength [150], and this guidance is adopted by most of U.S. states to increase system resilience against natural disasters. To obtain the optimal hardening strategies, risk-driven optimization models for hardening strategies can be established in consideration of different conditions [151]. In [152], a damage modeling framework is constructed to assess the effectiveness of grid reliability enhancement for power distribution systems. In [153], a two-stage stochastic model, in which the upper level optimizes which component needs hardening and the lower level deals with postdisaster repair scheduling, is established to quantify strategies. In [154], contingencies with temporal and spatial information are represented as a multi-stage multi-zone set, and the hardening problem is formulated as a defender–attacker–defender model, in which load shedding in the worst-case is minimized. In [155], a two-stage stochastic mixed integer model, in which line hardening is determined in the first stage and the operational cost is evaluated in the second stage, is proposed to design a resilience-oriented technique.

To use more green electricity, more renewable energy sources are integrated into power systems, introducing non-negligible uncertainty and variability. The uncertainty and variability pose great challenges to hardening strategies. In [156], a two-stage data-driven stochastic model is established to include the worst-case wind output scenario and system contingencies. In [157], a robust trilevel optimal line hardening

Table 7
Generation operation and optimization.

Category	References	Means
Conventional Generation	[82,84,85,133]	Comprehensive evaluation
	[86–89,134,135]	Coordinated scheduling of hydropower
	[12,91–95]	Unit commitment
	[90,136]	Unit maintenance
Renewable Energy	[69,96–98,109]	Photovoltaic power scheduling
	[62,99]	Wind power scheduling
	[100,101]	Photovoltaic power and wind power location scheduling
	[102,137,138]	Restoration source scheduling
Distributed Generation	[106,107]	Distributed generator location planning
	[62,108–110]	Distributed generation dispatch
	[111–114]	Recovery source scheduling
	[9,115–118,139–141]	Mobile emergency generator scheduling
Energy Storage	[60,62,98,100,123,142–144]	Fixed storage scheduling
	[124–126,145,146]	Mobile storage scheduling
Integrated Energy	[71,127–129]	Energy system resilience metrics
	[130–132,147]	Preventive and proactive planing and scheduling
	[148,149]	Restoration strategy

Table 8
Adaptation options for network.

Components	Events	Adaptation options	Effects
Substations	High Temperature	• Improve cooling systems for substations • Use more certified components that are suitable to high temperatures	• Improve efficiencies and reduce losses • Reduce failure probabilities
	Heavy Precipitation, Flood	• Elevate transformers and the corresponding components • Construct ring-shaped barrages	• Protect substations from flood and heavy precipitation
Lines, towers, poles	High Temperature	• Install underground cables or strengthen overhead lines. • Use certified components that are more resilient to high temperatures	• Improve line carrying capacities
	High wind speed	• Reinforce the existing components • Build more underground systems • Request higher design standards	• Prevent structural damages
Substations, lines, towers, poles	Icing, freezing rain	• Use high-pressure jet of hot water with fire hydrants and de-icing aircraft • Use infrared technologies, glycol-based liquids, and steam-based de-icing technologies	• Prevent structural damages

model in consideration of variable renewable resources is investigated to improve system resilience against worst N-k contingencies. With higher interdependence between gas grids and power grids, [158] investigates network hardening of the integrated gas-electric grids to improve system resilience against natural disasters, and a trilevel robust optimization model is investigated.

5.2.2.2. Reconfiguration. Network reconfiguration is also an effective means of reducing potential damages caused by natural disasters. Usually, network reconfiguration changes the system topology, and can make the networks less susceptible to natural disasters. With more advanced measuring devices, e.g., phasor measurement units and remote controls in power systems, network reconfiguration can be implemented to enhance power system resilience [159]. One effective way is to make decisions based on real-time system states under an unfolding sequential event. A Markov state-based decision-making model with the objective of mitigating loss of load by means of network reconfiguration is proposed in [12] and [160]. The system topologies including on/off states of feeder lines are modeled as Markov states, and the probabilities from one Markov state to another Markov state are determined by the component failures caused by the unfolding events. Based on Markov states, a recursive optimization model based on Markov decision processes, including the current cost and the expected cost in the future, is developed to make state-based actions at each decision time. To better evaluate structural resilience, a sequential steady-state security region (SSSR) is proposed in [13] to describe the operational region impacted by sequential weather events.

For the distribution systems, radiality constraints should be satisfied when performing reconfiguration. However, distribution system flexibility cannot be fully utilized when using some existing radiality constraints [161]. To address this issue, a new formulation for the radiality constraint, including topological and some related flexibility, is investigated in [162] to improve system resilience. In [163], the single-commodity flow constraint associated with the spanning tree is investigated to represent system radiality in distribution systems to increase the system resilience. Increasing distributed generators in the distribution systems changes the characteristics of traditional distribution systems without power sources, and this type of changes associated with network reconfiguration can greatly improve system survivability in the face of natural disasters. In [109], an outage management

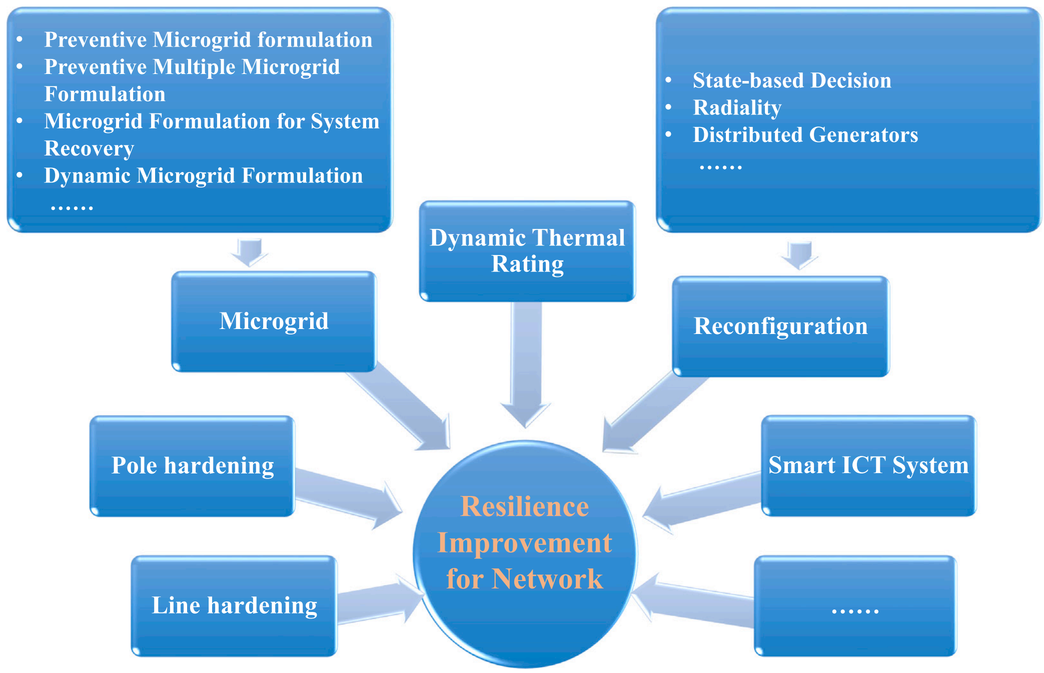

Fig. 4. Network operation and optimization for system resilience improvement.

strategy in consideration of distributed energy resources and network reconfiguration is proposed to minimize operational costs for loss of load. In [101], a two-stage stochastic optimization model, in which the first level is to determine line outage scenarios and the second level is to optimize network reconfiguration, is proposed to increase distribution system resilience. In [164], resilience-based coordinated storage allocation in consideration of distribution network reconfiguration is optimized in severe contingency conditions.

5.2.2.3. Dynamic thermal rating implementation. Dynamic thermal rating (DTR) indicates that the line capacity is dynamically varying according to the external environmental conditions [165,166], e.g., ambient temperature, wind speed, rainfall, and solar radiation, which could have obvious fluctuation due to natural disasters and extreme weather events. An increased dynamic thermal rating (DTR) can improve the capacity of transmission lines, and enables a more flexible power flow [167–169]. This makes power networks more available for power transfer and allows more loads to be connected with the grid to ride through an emergency like a weather-related event, and in consequence improves system resilience. Currently, the DTR implementation has not yet gained wide deployment by utilities. Usually, three primary parts [170], i.e., DTR devices that monitor system conditions, communication devices that receive/transmit data, and software that quantifies the line's thermal capacity, are included to implement the DTR technology, which will be an effective means to enhance system resilience against natural disasters and extreme weather events.

5.2.2.4. Microgrid. Microgrids are considered as localized small power systems, which have the advantages of easy controllability compared to conventional distribution systems. Because microgrids have higher capabilities of power supply to load, many studies focus on system resilience enhancement by means of constructing microgrids.

In the face of natural disasters, microgrid formulation is an effective means to reduce potential damages. There are many studies on this topic. Usually, the common concept is to construct appropriate microgrids with the objective of minimizing the number of vulnerable lines in service at the event onset [171]. In [172], a two-stage robust model for pre-event microgrid formulation is established to minimize the potential outages due to natural disasters. To guarantee survivability of critical loads in emergency periods, microgrids with appropriate status of distributed generators are constructed in [173]. In consideration of multiple energies in networks, multiple energy carrier microgrids can be used to enhance system resilience [147,174].

During the events, based on updated information, dynamic formulation of microgrids can be one of effective means to reduce the potential loss of load. In [175], dynamic microgrid formations associated with distributed generators are investigated to increase distribution system resilience in the face of natural disasters. [176] focuses on a computerized tool that keeps self-sustainable load by dynamically scheduling microgrids. Some multi-level models, e.g., two-level and tri-level models, are proposed to dynamically construct microgrids. For example, [177] proposes a two-stage stochastic model for dynamic formulation of microgrids with uncertain renewable energy sources, and [178] investigates a tri-level model in consideration of dynamic microgrid formulation with multiple energy sources to improve system resilience.

Event though preventive and proactive strategies could be implemented before and during natural disasters, outages cannot be completely avoided. Microgrid formulation is also one of effective ways to supply critical loads and restore the system to normal states as quickly as possible. [179] presents a hierarchical outage management scheme based on multiple microgrid formulation. A heuristic approach for microgrid formation after disturbances is investigated in [180] to deal with computational intractability caused by a large scale system. When constructing microgrids, the capacities of distributed generators have great impacts on microgrid operation, and in consequence have negligible impacts on system resilience against natural disasters. In [181], dynamic performances of distributed generators with limited capacities in microgrids are incorporated as constraints into the restoration model. In practice, system conditions are constantly changing, and one more effective means is to construct microgrids for load recovery dynamically as the conditions changes. Table 9 summarizes network operation and optimization.

5.2.2.5. Smart ICT system. Energy supply systems are changing, and increased distributed energy sources, e.g., wind power, photovoltaic, and electric vehicles, connected to the conventional systems are typically area-wide distributed and require to be controlled rapidly by means of Energy Management System (EMS) or MicroGrid Supervisory Controller

Table 9
Network operation and optimization.

Category	References	Means
Network Hardening	[64,151–155]	Hardening strategies for lines and poles
	[156–158]	Hardening strategies in consideration of uncertainties
Reconfiguration	[160]	State-based strategies
	[161–163,188]	Radiality constraint investigation
	[101,109,164]	Distributed generator dispatch
Dynamic Thermal Rating	[167–169]	Increase dynamic thermal rating
Microgrid	[171–173,189]	Preventive and proactive microgrid formulation during natural disasters
	[147,174]	Preventive and proactive multiple microgrid formulation during natural disasters
	[175–178]	Dynamic microgrid formulation during natural disasters
	[142,179–181,190]	Microgrid formulation for load recovery after natural disasters
	[14,191]	Dynamic microgrid formulation for load recovery after natural disasters
Smart ICT System	[182,183,185]	Smart ICT systems

Table 10
Adaptation options for load.

Components	Events	Adaptation options	Effects
Loads	Temperature Changes	• Improve energy performance standards for electricity-using appliances • Effective demand responses • Employ international standard energy management • More absorption chilling or evaporative cooling systems	• Improve efficiency and reduce losses • Reduce peak demands

(MGSC) with modern information and communication technologies (ICT). A smart and strong ICT system could affect the system capacity of dealing with disasters. To build a strong backbone ICT system in modern power systems, the optical fiber composite overhead ground wire (OPGW) on the top of transmission towers is one of popular structures. Different ICT topologies based on existing system structures could have different capacities against extreme events. Usually, data-driven metrics are employed to evaluate these impacts [182,183]. A qualitative evaluation for different ICT topologies is provided in [184], and an emulation-based method for evaluating ICT system resilience in disaster situations is proposed in [185].

Associate with smart ICT systems, self-healing systems could locate and analyze faults, and then execute appropriate corrective actions. Usually, self-healing functions can be achieved by means of smart metering units, synchrophasor measurements, intelligent fault identification modules, network reconfiguration, and microgrid formulation [186,187].

5.3. Load perspective

5.3.1. Adaptation options for load

The possible adaptation options are listed in Table 10. The critical factors would be presented.

5.3.2. Load operation and optimization

Many studies focus on system resilience from the perspective of load operation and optimization, as shown in Fig. 5. Power system loads consist of a huge number of power components, which are affected by various factors. However, one of critical factors that result in extreme high load peak is extreme high/cold temperature. Effective ways to improve system resilience against natural disasters from the perspective of load include load shedding, load shifting and demand response, which need appropriate scheduling on load locations and load

Table 11
Load operation and optimization.

Category	References	Means
Load Shedding/Shifting	[189,192,193]	Load shedding
	[108]	Load shifting
Demand Response	[177,197]	Scheduling with microgrids
	[198]	Building energy scheduling
	[199]	Electric vehicle scheduling
	[47,200]	Responses to different events
	[201,202]	Load restoration after outages

capacities. In [12], proactive state-based strategies with minimizing load shedding at appropriate buses are investigated to improve system resilience against an unfolding typhoon. In [192], load shedding associated with controlled islanding is proposed as the last resort to determine the splitting points just in case a total black due to natural disasters. In [108], load shifting associated with distribution network reconfiguration and distributed generator scheduling is investigated to increase resilience and economic profits in smart grids. Natural disasters could result in rapid frequency decline, which might cause blackouts, and traditional load shedding may fail to respond this type of frequency decline. In [193], a new dynamic-adaptive load shedding mechanism is presented to ensure appropriate load curtailment within acceptable frequency declines. Demand response is one of effective resorts to change power load curve [194–196], which could benefit to system resilience improvement [47]. Associated with microgrid formulation, demand responses for aggregated loads are implemented in [197] and [177] to improve system resilience. Furthermore, demand responses with regard to urban building energy and electric vehicles are investigated in [198] and [199] to increase power system resilience under various extreme weather scenarios. Table 11 summarizes load operation and optimization.

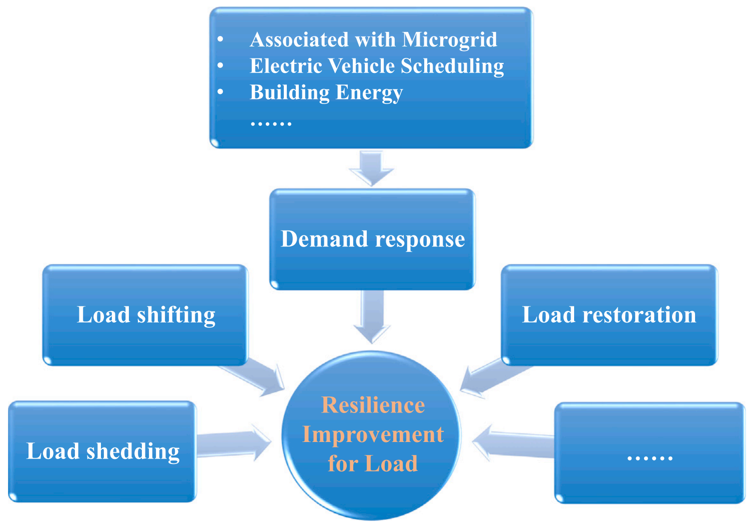

Fig. 5. Load operation and optimization for system resilience improvement.

6. Discussion on future resilience improvement

Based on the literature review, many points are still in their infancy with regard to power system resilience improvement, and they can be promising research points, as listed in Fig. 6, in the future.

6.1. From perspective of generation

6.1.1. Multiple energy systems

Due to increasing concerns on climate changes, traditional power systems are expected to have more low-carbon and sustainable energy sectors. In China, carbon neutrality by 2060 is one of critical goals with regard to energy policy, and the Chinese government has implemented a series of policy measures to reduce greenhouse gas emissions. Constructing multiple energy systems provides an effective way to reduce carbon emissions by integrating different forms of energy across multiple pathways, scales and time horizons. However, appropriate system scheduling and optimized strategies are needed to guarantee high system resilience. One typical example is Texas power outage in 2021. Integrated gas-power systems were under extreme cold weather, which caused severe outages in Texas due to inappropriate system operation. Therefore, it is important to investigate systematic frameworks and techniques for real-time state-based system strategies against natural disasters.

In addition, the time scales of multiple energy systems are usually different. This indicates that their responses to disturbances have great distinctions. Typically, natural disasters usually are sequential and persistent during one period. This would have a great challenge to coordinate multiple energy systems with different time-scale responses. Currently, most of research studies have not included this point. Therefore, this point is one of promising research directions in the future.

Usually, multiple energy means multiple energy suppliers, and each supplier expects to have its own maximum revenues. Under normal conditions, this question is usually considered as a game-based problem. In the face of natural disasters, two challenges need to be addressed. The first one is how to include sequential and uncertain impacts of the natural disasters on multiple energy supplies in the game-based model, and the second one is how to solve the game-based model with complicated operational constraints. Therefore, this point is also one of promising research directions.

6.1.2. Uncertainty caused by renewable energy

Carbon neutrality and low-carbon energy sectors inevitably result in high penetration of renewable energy, introducing more uncertainties into the systems. Currently, many studies focus on system operation with uncertain renewable energy under normal conditions. However, if a system is in the face of an unfolding extreme weather event, there are two critical issues to be considered when making optimal strategies. The first one is that the system under an unfolding extreme weather event may be not strong as the normal conditions, and the second one is that renewable generation could be affected by the unfolding extreme weather event. In consideration of these two issues, the conventional stochastic programming-based strategies for renewable energy under normal conditions are usually improper to high penetration of renewable energy in the face of an unfolding extreme weather event.

In addition, coordinated scheduling for different uncertain energy sources in consideration of uncertainties caused by extreme weather events and geographic restriction is a topic worth studying. For example, there are many cascaded hydropower stations in the southwest of China, and there are photovoltaic power stations nearby these cascaded hydropower stations. Extreme heavy precipitation would have great impacts on power generation of cascaded hydropower stations in consideration of spatiotemporal changes of reservoir forebay water levels, net water heads, and reservoir tailrace water caused by sequential precipitation. Furthermore, sequential heavy precipitation would affect photovoltaic power outputs. How to model these uncertain impacts and coordinate these sources is critical, and is one of promising directions.

6.1.3. Instability caused by renewable energy

Usually, wind power and photovoltaic power are connected to networks by means of power electronics, which decrease system inertia and reduce the grid strength against disturbances. These could jeopardize system dynamic stability. High penetration of wind power and photovoltaic power would have negative impacts on system synchronous inertia and system stability. For a system under an unfolding natural disaster, system conditions, including system topology, power generation, and load demand, may have persistent changes, and in consequence result in persistent changes of system inertia. This would challenge system operation in the face of an unfolding natural disaster, and this is a topic worthy of investigation.

6.2. From perspective of networks

6.2.1. Cyber–physical systems

Conventionally, system operators mainly focus on resilience investigation from the perspective of physical systems. Recent years have

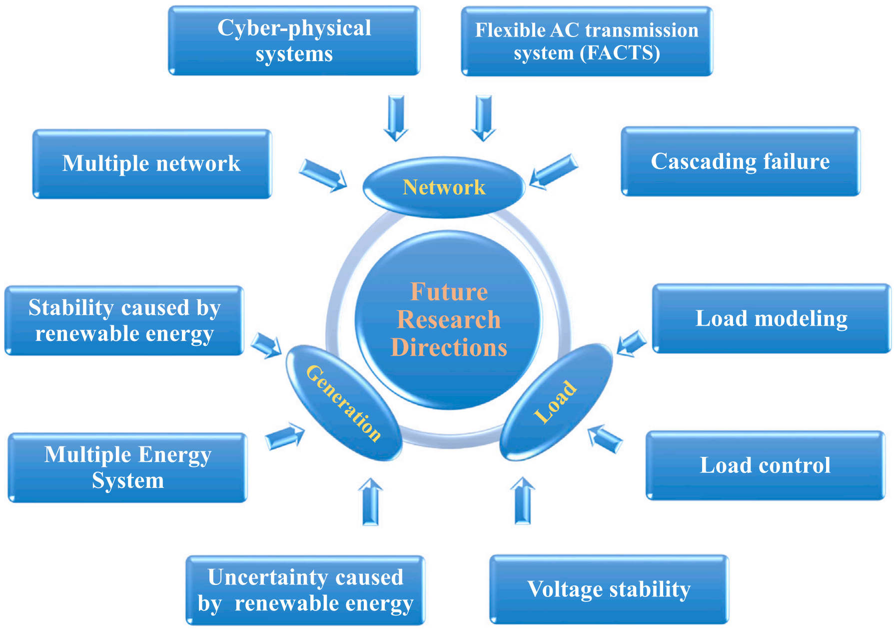

Fig. 6. Future Research Directions.

witnessed rapid development in information communication technologies, with which power systems are transformed from conventional physical systems to cyber–physical systems. Similar as physical systems, cyber systems also have wide-area geographical characteristics, and many of components in cyber systems are directly exposed to external environment, which makes cyber systems vulnerable to natural disasters and extreme weather events. System monitoring and remote control are critical functions for cyber systems. When cyber–physical systems are in the face of extreme weather events, unavailability of some parts of cyber systems due to failures caused by extreme weather events could lead to incomplete information and control failure. Incomplete information could fail the system operators know the system states that are critical to make decisions, and control failure means that the optimized strategies cannot be implemented as scheduled. Therefore, how to consider the impacts of extreme weather events on cyber–physical systems is one of critical issues with regard to system resilience improvement.

6.2.2. Flexible AC transmission system (FACTS)

During an unfolding natural disaster, appropriate power flow distribution could help the system avoid severe damages caused by disasters. In the power systems, flexible ac transmission system (FACTS) devices can be used to increase the power-transfer capability and to change power flow over designated routes. With the development of modern power electronics technologies, more and more FACTS devices, e.g., static synchronous compensators, static synchronous series compensators, and unified power flow controllers, can be applied in the power systems associated with conventional control strategies to increase the power system resilience against natural disasters.

6.2.3. Cascading failure

With the increasing scales of the power systems, some initial disruptions could result in blackouts due to failure propagation throughout the systems. We have already witnessed many severe cascading blackouts, e.g., the 2003 U.S.- Canadian blackout, the 2011 Arizona-Southern California blackout, and the 2019 Venezuelan blackout. Usually, natural disasters, e.g., typhoons and wildfires, are sequential events, and this indicates that the disruptions of these events on the power systems are also sequential. Some sequential failures could be caused on the trajectories of these events. One of these sequential failures may trigger cascading failures in consideration of unnormal conditions under natural disasters. Therefore, when making resilient strategies against natural disasters, potential cascading failures are necessary to be included in the problem.

6.2.4. Multiarea networks

Currently, system expansion, markets, and multiple energy systems drive the power system into a multi-area interconnected system. Conventional centralized methods cannot be directly used for multi-area interconnected systems in consideration of information privacy, extensive communication burdens, and specific jurisdictional mandates. Boundary restrictions could complicate the problems such as how to coordinate the strategy of each area to enhance system resilience from the perspective of each area, and this is a topic worthy of investigation.

6.3. From perspective of loads

6.3.1. Load modeling and control

Accurate load modeling plays an important role in power system secure and efficient operation, and it is critical to load control, e.g., load shedding, load shifting, and demand response, in the face of an unfolding natural disaster. However, accurate load modeling is an issue of which the complexity has been internationally acknowledged. In consideration of mass power electronics, smart loads, responsive loads, how to develop an integral load modeling technique, which includes different classifications and regions of loads, is a crucial task to ensure reliable system operation, and in consequence ensure a resilient system in the face of natural disasters. In addition, developing techniques for fast and accurate bulk load control is also critical to load shedding, load shifting, and demand response in consideration of mass power electronics, smart loads, and responsive loads. This point is one of critical research directions.

6.3.2. Voltage stability

Voltage stability is described as a capability of a power system to maintain steady voltage at each bus after disturbances, and it is related to the ability to supply power to load. According to time scales, it can be divided into short-term voltage stability and long-term voltage stability. Short-term voltage stability includes dynamics of fast acting load components, e.g., inverter-based generators, electronically controlled loads, induction motors, etc. Long-term voltage stability includes slower acting equipment, e.g., thermostatically controlled loads and tap-changing transformers, and this type of voltage instability could be caused by transmission/generation device failures and sustained load increases. An unfolding extreme weather event results in persistent disturbances to generators/lines/loads, and this could result in voltage stability if no appropriate actions are implemented. In addition, it is necessary to restore system as quickly as possible during the blackout. During this period, the network is usually not strong as normal conditions, and generation may not have enough reserves. Inappropriate system restoration strategies could further jeopardize the system conditions, and in consequence result in voltage instability. Therefore, how to include voltage stability into the power system resilience is one of important research directions.

7. Conclusions

This paper reviewed power system resilience from the perspective of generation, networks, and loads, respectively. First, typical outages caused by extreme weather events and natural disasters are statistically presented, and the statistics show that wind storm, ice storm, and thunderstorm have higher percentages than wildfire, high temperature, and earthquake with regard to their occurrence and affected people. The impacts of extreme weather events and natural disasters, e.g., flooding, heavy precipitation, drought, high temperature, icing, low temperature, storm, lightning, earthquake, and high speed wind, on generation, networks, and loads are qualitatively presented. Second, the quantitative impacts of extreme weather events and natural disasters on component efficiencies and component failure probabilities from the perspective of generation, networks, and loads are presented. Based on these quantitative impacts, it is possible to investigate appropriate strategies against these extreme weather events and natural disasters. Third, adaptation options for component resilience improvements are introduced, and then detailed resilience enhancement strategies for generation, networks, and loads are systematically presented. For power generation, the strategies on conventional generators, renewable energy, distributed generators, energy storages and integrated energy are discussed. For the networks, the strategies on network hardening, reconfiguration and microgrid formulation are discussed. For the loads, strategies on load shedding, load shifting and demand response are presented. In this review, the detailed mathematical models for system resilience and the corresponding algorithms are not discussed.

Based on the review, some critical points related to system resilience from the perspective of power generation, networks, and loads are suggested:

- Different kinds of natural disasters have different impacts on various power sources, and in consequence determine power production. Coordinated scheduling of different power sources is necessary and effective to improve generation resilience. Specifically, state-based emergency strategies, different time scales of multiple energy systems, multiple energy suppliers in multiple energy systems, uncertainty/instability caused by renewable energy could complicate the problems when making system resilience strategies.
- System networks are important to bridge generation and load, and they need to have strong resilience in the face of varying and uncertain impacts caused by natural disasters by means of system hardening, reconfiguration implementation, microgrid formulation, etc. Furthermore, cyber–physical systems, flexible AC transmission systems, cascading failures, and multiarea networks pose great challenges to system decision-making, and how to construct a resilient network in consideration of the above factors is one of future directions.
- Increasing smart/responsive loads have outstanding potential regulating ability for enhancing power system resilience. Load modeling accuracy and load controllability have also great impacts on system operation and strategy implementation, and are critical to enhance power system resilience in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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