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Resilient power grid for smart city

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ABSTRACT

Modern power grid has a fundamental role in the operation of smart cities. However, high impact low probability extreme events bring severe challenges to the security of urban power grid. With an increasing focus on these threats, the resilience of urban power grid has become a prior topic for a modern smart city. A resilient power grid can resist, adapt to, and timely recover from disruptions. It has four characteristics, namely anticipation, absorption, adaptation, and recovery. This paper aims to systematically investigate the development of resilient power grid for smart city. Firstly, this paper makes a review on the high impact low probability extreme events categories that influence power grid, which can be divided into extreme weather and natural disaster, human-made malicious attacks, and social crisis. Then, resilience evaluation frameworks and quantification metrics are discussed. In addition, various existing resilience enhancement strategies, which are based on microgrids, active distribution networks, integrated and multi energy systems, distributed energy resources and flexible resources, cyber-physical systems, and some resilience enhancement methods, including probabilistic forecasting and analysis, artificial intelligence driven methods, and other cutting-edge technologies are summarized. Finally, this paper presents some further possible directions and developments for urban power grid resilience research, which focus on power-electronized urban distribution network, flexible distributed resource aggregation, cyber-physical-social systems, multi-energy systems, intelligent electrical transportation and artificial intelligence and Big Data technology.

KEYWORDS

Resilient power grid, smart city, extreme event, resilience metric, resilience enhancement strategy.

As the global city-scale expands unceasingly and the urban function becomes complex, modern cities play a more and more key role in energy consumption, pollutant emissions, and carbon emission levels constantly. According to UN Habitat, modern cities consume 78 percent of the world's energy and produce more than 60 percent of greenhouse gas emissions[1]. Environmental problems associated with climate change become increasingly serious, accompanying with kinds of extreme weathers and the public health events. Furthermore, human-made cyber-attacks[2], terrorist attacks[3], and military confliction[4] pose serious threat to global energy security. This high impact low probability (HLIP) events introduce severe challenges to the resilient running of modern city.

With the rapid development and broad application of information and communication technology, urban intelligence levels have been enhanced significantly. Various smart urban infrastructure also make the concept of smart city form, which gradually draws lots of attentions from academia and industry[5]. The main purpose of a smart city is to support urban economic development while also enhance citizens' quality of life by utilizing smart technologies. The characteristics of a successful smart city can be determined as safe, sustainable, efficient, low-carbon, and resilient, which asks the city has the similar smartness like human beings. A safer, lower-carbon, and cleaner resilient urban power grid is of importance to realize the smart city[6]. As the electricity energy system should supply nearly all other urban infrastructure, the first step to ensuring resilient operation of a city is to ensure a resilient power grid. An ideal smart city which is supported by a resilient power grid is shown in Figure 1.

Resilience is defined as the "the ability of a system, community or society exposed to hazards to resist, absorb, accommodate to and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions", according to the United Nations Office for Disaster Reduction[7]. From the perspective of urban power grid, the resilience has the four characters, namely anticipation, absorption, adaptation, and recovery[8]. Anticipation means a resilient power grid should have the capability to forecast, simulate, alert, adapt, take precautions, defend, and resist risk before and during the extreme events[9]. Absorption means a resilient urban power grid should maintain key functions and security of critical components through offsetting or isolating the impact of extreme events[10]. Adaptation represents the urban power grid is able to self-organization to achieve basic functional repair before implementation of recovery measurements[11]. Recovery is the capacity of urban power grid to recover partial loss of functionality to a reasonable level timely after damaged[12].

Comparing to other similar concepts such as reliability, vulnerability, robustness, flexibility, risk assessment, contingency analysis, and adaptability, power grid resilience analysis is based on the trend of network topology changes, which is influenced by the severity of HILP events, and so it exhibits a dynamic behavior as shown in Figure 2[13,14]. It can be considered as a higher requirement for the concept of reliability which focus on the usual failure with high probability and low impact rather than extreme events. Also, resilience analysis progress contains the traditional risk assessment and contingency analysis whose methods and quantification metrics can be integrated in it. In addition, entire resilience analysis progress of urban power grid consists of many time states, each of which has different resilience objectives and characteristics. At different time states, some parts of vulnerability and robustness anal-

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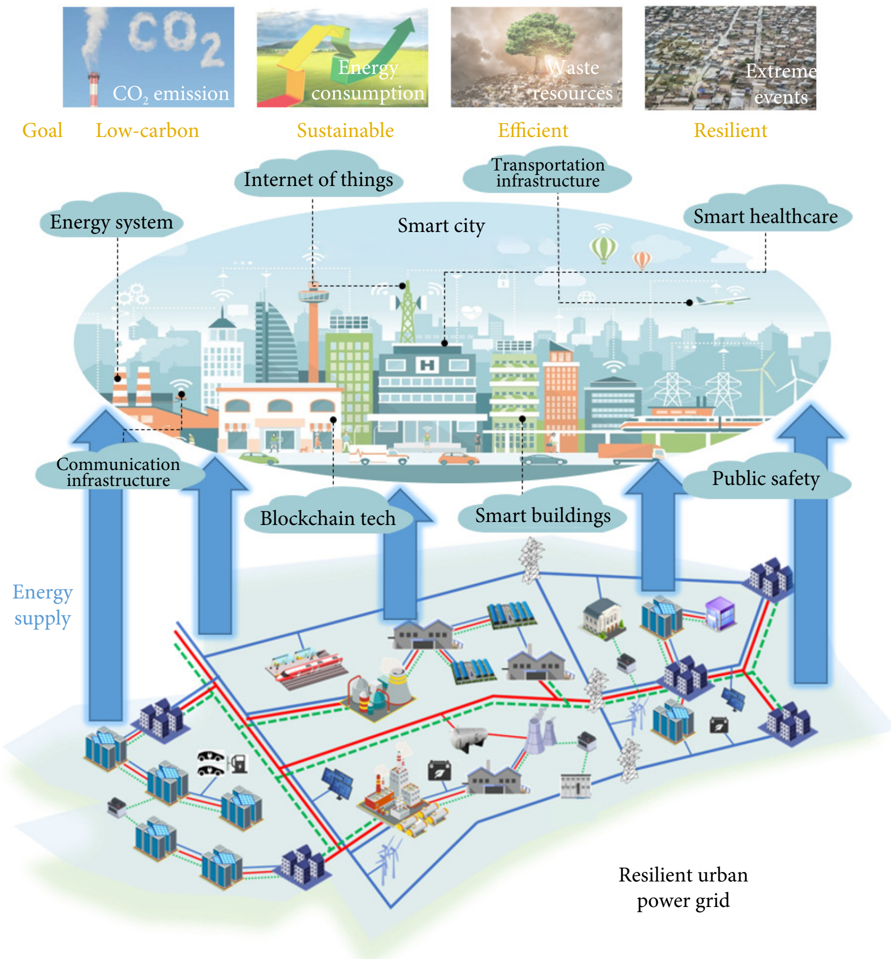

Fig. 1 An ideal smart city supported by a resilient power grid.

ysis of power systems have the same direction and effectiveness. And the resilient operation of urban power grid can be supported by fully utilizing grid's flexibility and adaptability against HILP extreme events. Thus, resilience in power systems is an integrated concept brings some demands and functions of traditional analysis methods and concepts together, aiming to keep the safety of power grid under more terrible conditions.

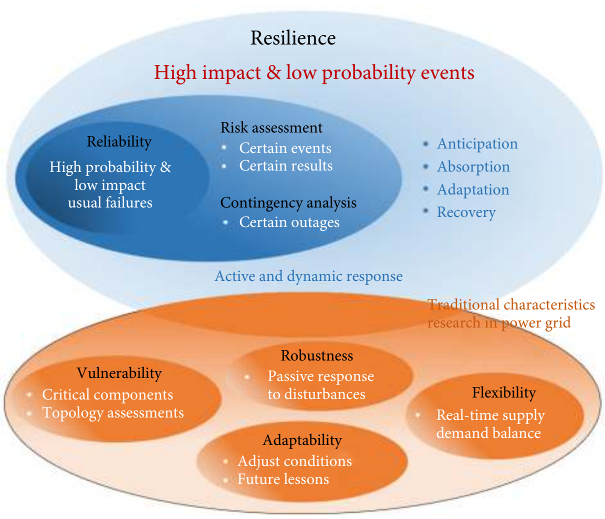

Fig. 2 The characteristics of resilience versus other similar concepts in power grid.

Meanwhile, the urban power grid is increasingly coupled with other urban infrastructures, such as the communication system[15], the transportation system[16], and the integrated energy system within multi-energy flow[17–20]. The normal operation of urban infrastructure systems is supplied by urban power grid and the dependency on it deepen as electrification increasing. Thus, different infrastructures can be considered as potential resilience support and energy resource for power grid resilient operation by smart city technologies. Likewise, a resilient grid can reduce the risk of collapse of other urban infrastructures against HILP events, to enhance the overall resilience of the city.

This paper makes a comprehensive review on the HLIP extreme event categories that influence urban power grid, resilience evaluation frameworks and metrics, and advanced various resilience enhancement strategies. Finally, this paper proposes and discusses some further possible directions and developments for urban power grid resilience research.

1 Impacts of extreme events on power grid

HLIP extreme events that pose severe risks to resilient power grid can be divided into three main categories, namely extreme weather and natural disaster, human-made malicious attacks, and other global black swan event (e.g., Covid 19 Pandemic, energy crisis), as shown in Figure 3. Among them, the impacts of extreme weather and natural disaster to urban power have more adequate previous studies, which is the mainstream research direction of resilience. Damages caused by extreme weather and natural disaster

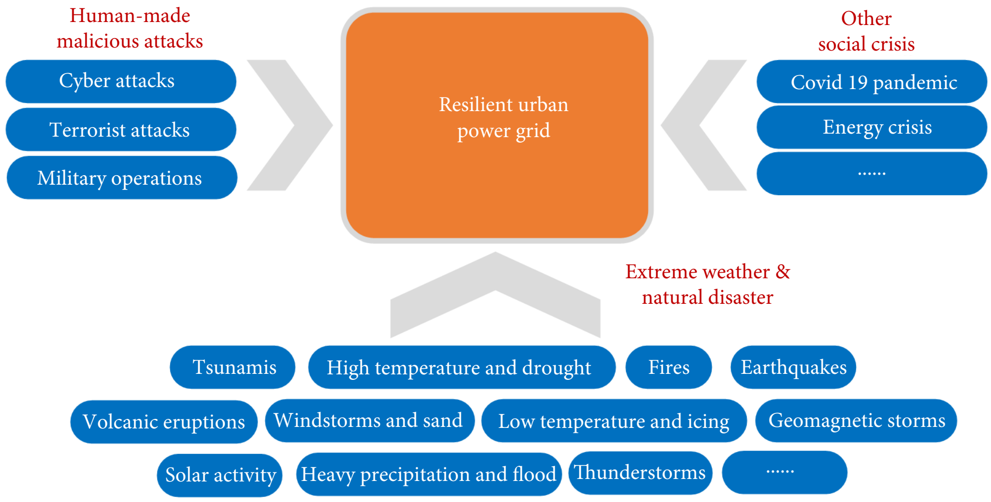

Fig. 3 Extreme events impact the resilient urban power grid.

to urban power grid are most common, some of which will lead to large-scale urban power grid collapses. Also, two other types of extreme events are creating increasingly serious challenges to resilient urban power grid.

1.1 Extreme weather and natural disasters

Today, with increased human economic activity, extreme weather events are trending to be more frequent than in previous historical periods, creating unprecedented challenges to the resilient operation of infrastructure in cities. Extreme weather events generally include high temperatures, drought, fire, low temperatures, icing, heavy precipitation, flood, windstorms, sandstorms, thunderstorms, earthquakes, and other geological or astronomical natural disasters.

1.1.1 High temperature and drought

High temperature out of expected is a typical form of extreme weather, which has a negative impact on resilient operation of urban power grid. First, excessive ambient temperatures can reduce temperature differences during combustion, decreasing the efficiency of boilers, turbines, and generating units[21]. While thermal power plants require cooling water for circulation and cooling during operation, drought may reduce their power production or shutdown[22]. In addition, hydroelectric power generation would be greatly affected by high temperatures and drought, and the reduction in available water resources due to drought can directly reduce the output of hydroelectric generating units[23]. High temperature also makes PV modules less efficient and accelerate solar panel aging[24], while cooling systems are less efficient[25], all of which would reduce overall solar power output.

From a load-side perspective, there is a strong positive correlation between electricity demand and temperature in high-temperature environments. Studies have shown that for every degree of ambient temperature rise during peak summer electricity consumption, the urban electricity load rises by 3%–7%. Excessive cooling and air conditioning compliance with demand can significantly increase peak grid loads and the risk of unexpected energy supply events[26]. Even if the high temperature may not directly damage the structure of energy infrastructure, high tension of power supply caused by high temperature and drought evidently make a resilience crisis of urban power grid. It will become more vulnerable to other types of potential or concurrent HILP extreme events, which should be paid more attention by operators of a smart city.

1.1.2 Fires

Drought also leads to an increased chance of fires. Fires can directly destroy network components such as transmission and distribution towers, or cause outages due to ash ionization pathways, threatening the ability to supply power to the grid. For example, New Mexico and California in the United States have experienced large-scale power incidents caused by wildfires[27].

1.1.3 Low temperature and icing

Low-temperature environments can, first and foremost, adversely affect wind turbines' constituent materials and internal mechanical properties[28]. Low ambient temperatures in cities can lead to icing formation, increasing wind turbine downtime[29]. In cold winters, extreme ambient low temperatures can drive up system power peaks, which will reduce the degree of grid resilience and increase the risk of outages. Severe icing and snow even will directly destroy the components of power grid, leading to large-scale black out. For instance, in southern China, the grid suffered severe snow and ice events in 2008[30]. More recently, widespread severe outages with wind turbines damaged due to the extreme low temperature occurred in Texas in the winter of 2021[31].

1.1.4 Heavy precipitation and flood

Heavy precipitation can lead to the water spills of reservoir, flooding downstream of the reservoir[32]. Moreover, there is a high risk of severe damage to dam structures from debris flows and alluvial deposits generated by flooding[33]. Hydro generator power will decrease due to structural damage. In addition, floods will directly damage the resilient operation of the power grid in the smart city. For instance, lightning strikes and electrocution from downed power lines caused by the record rainfall made some of the deaths and large-scale blackouts in Beijing, 2012[34]. And the massive flood destroy the urban electricity supply and internet service in Zhengzhou, 2021[35].

1.1.5 Windstorms and sand

Extreme storms often exceed the maximum operating conditions for which wind turbines are designed and can cause damage to wind turbines. Hurricanes and typhoons pose serious hazards to wind turbine plant operations worldwide[36,37]. Moreover, sandstorms caused by wind storms can increase the time workers take to clear photovoltaic mirrors and reduce the power generated[38].

More seriously, windstorms are often accompanied by other extreme weather such as heavy precipitation, flooding, and lightning. They significantly impact the urban grid structure and can damage power overhead lines, transformers, and towers[27,39]. Damage to urban transmission and distribution networks can lead to a resilience reduction in power transmission capacity, reducing urban energy resilience. For instance, a large-scale blackout occurred in Australia, 2016[40], which is caused by windstorm and accompanying extreme weather.

1.1.6 Thunderstorms

Thunderstorms are also a significant cause of damage to urban transmission and distribution networks. Although transmission and distribution networks are generally equipped with insulation and shielding to prevent lightning damage, thunderstorms can also cause damage to grid components through charge transfer, high peak currents, and electromagnetic pulse overvoltage. Especially in less economically developed areas, such as Java and Bali, thunderstorms often cause grid damage to power outages[41].

1.1.7 Other natural disasters

In addition to the extreme weather mentioned above caused by increased atmospheric activity due to global climate change, other geological or astronomical natural disasters can also adversely affect urban grid operations, including earthquakes[42], solar activity[43], geomagnetic storms[44], tsunamis[45], volcanic eruptions[46]. The probability of these black swan events[47] is very dependent on the city's geographical location. Thus, local grid operators often need to specify resilience enhancement policies based on the specific urban natural characteristics and economic development level.

In general, extreme weathers and natural disasters can trigger cascading failures of urban power grid[48] and hurt the resilient operation of smart cities at three levels: the generation side, the grid side, and the load side. It creates new challenges for the intelligent operation of modern distribution networks in smart cities.

1.2 Malicious attacks

Active malicious attacks on city power grids are generally planned by criminal or hostile organizations. These extreme events often target urban critical cyber and physical infrastructure, which can be classified into three categories: cyber-attacks, terrorist attacks, and military operations.

1.2.1 Cyber attacks

The development of modern smart grid technology has made cyber-physical systems (CPS) a reality[2]. CPS is subject to cyber-attacks from various sources, including threats from outside the system, such as terrorist organizations, foreign intelligence services, and hackers. These hostile forces steal the identities of legitimate users through spam, phishing, and malicious programs to make financial gains and disrupt the public. Besides, there are also threats from within the system, such as unrestricted access to the target system by system administrators to carry out damage, or more seriously, illegal operation of field devices by operations and maintenance personnel.

Cyber-attacks have occurred in recent years and caused significant harm to the grid. In 2010, the Stuxnet worm attacked Siemens' SIMATIC WinCC system[49]. In 2012, Schneider Electric's power SCADA system was hacked[50]. In 2015, a cyber-attack on the Ukrainian grid caused a massive blackout[51]. A major cyber-attack occurs on the Israeli power grid in 2016[52]. US power companies was blackmailed by a Russian hacker group in 2017[53].

1.2.2 Terrorist attacks

An analysis of the global terrorism index (GTI) of current global terrorist activity through big data reveals that global terrorist activity significantly affects Middle East and UK[54]. This result indicates that terrorist attacks continue to threaten cities' security in developed and developing regions. The US Committee on Science and Technology for Countering Terrorism claimed: "The nation's electric power systems must clearly be made more resilient to terrorist attacks"[55].

Modern cities are responsible for keeping local power systems safe under rampant terrorist attacks. Terrorists hope to provoke panic in crowds through uncertain terrorist activity[56], and the spread of panic can be exacerbated by causing a massive power outage. Terrorists may plan unpredictable attacks on complex urban transmission and distribution networks in cities to trigger large-scale cascading failures[57]. Therefore, governments must increase the resilience of urban power grids when the public is exposed to potential terrorist threats, including increased investment, as summarized by the US National Research Council in a workshop conducted in 2013[58].

1.2.3 Military operations

Modern military operations often directly claim an economic interest in energy[59]. Moreover, as modern military installations become more electrified, the sustainability of the military is often determined by the supply ability of electrical energy[4]. Meanwhile, due to the long-range and wide-scale characteristics of modern energy supply networks, the shutdown of energy production due to military conflicts in localized areas can also create energy supply constraints in faraway modern cities. For example, the Russian–Ukrainian military conflict in 2022 not only led to power outages in major cities within the country of Ukraine but even to creating power supply gaps in European cities[60]. Short-term power shortages have also accelerated the transformation of national energy policies in Europe[61].

In addition, other infrastructure such as urban electrical transport networks can help to defense malicious attacks to grid[62]. Existing research generally uses vulnerability or resilience assessment methods for these malicious attacks and flexible defenses using available urban resources[2].

1.3 Other social crisis

The Covid 19 pandemic has affected the world from 2020 to the present. Covid 19 poses a severe threat not only to human life and health but also to energy security in all cities of the world[63]. In general, the reduction in economic activity due to Covid 19 reduces the electricity load in cities[64]. In Spain, the overall electricity demand of the society in the context of a pandemic produced a significant decrease and a significant increase in electricity demand uncertainty[65]. In some areas, Covid-19 also has the potential to link up with other natural hazards, such as hurricanes, and together have a devastating impact on grid resilience[66]. As the Covid 19 pandemic is receding globally, countries worldwide began to gradually de-quarantine and adopt economic stimulus policies. Covid 19 affected Malaysia's renewable energy strategy, delaying its solar energy strategy[67]. In Europe, the energy shortage caused by Covid 19 has recognized the importance of resilient grids. It has led European countries to plan policies to increase system flexibility and resilience during the epidemic[68]. In the face of the impending post-epidemic era, the US state of Connecticut has adopted Tree-trimming operations (TTOs) in space to enhance local grid resilience[69]. In the future, urban electricity demand will predictably return to its peak on a global scale[70]. The shortage of power operations and maintenance staff caused by

Covid 19 will pose new challenges to resilient urban grid operation during the future global economic recovery.

Meanwhile, the global energy crisis also has significant impacts on resilient operation of power grid in modern city[71]. Soaring international prices for coal, oil and gas[72] will exacerbate energy shortages within the city. In Europe, the price of natural gas in August 2022 was already over $3,100 per 1,000 cubic meters, which has an increase of 610% year-on-year as measured by the Dutch TTF market[73]. Meanwhile, EU member states generally adopt relatively aggressive renewable energy policies, which will undoubtedly reduce the resilience of power grid in major EU cities under extreme weathers. In addition, the energy crisis will also make urban electricity prices increasingly volatile. German power prices for next year on August 29, 2022, which are considered Europe's benchmark, briefly jumped above € 1,000 per megawatt hour before falling back to € 840 per megawatt hour[74]. When electricity prices in EU keep smashing records and highly volatile, the corresponding costs of resilience-supporting ancillary services and the citizens' concerns about the security of energy supply in cities will rise accordingly. In summary, urban power supply capacity will also be reduced because of the energy crisis, and rising electricity prices will contribute to increase the cost of the urban resilient operation. To clearly show the realistic results of HILP extreme events, some typical examples of the adverse effects of different extreme events on urban power grid is list in Table 1.

2 Resilience evaluation framework

There is no consensus on the standard of grid resilience, and the resilience evaluation is classified as qualitative and quantitative. Qualitative methods focus on long-term planning and decision making, which use checklist and questionnaires[75], matrix-based approach and influence of humans[76] to assess resilience of power grid. However, qualitative methods are lack of numerical descriptors and probabilistic approaches. Thus, this paper focus on quantitative resilience assessment metrics of power grid in smart city.

2.1 Resilience curve

Resilience curve is a widely used method to make a quantitative assessment for the power grid. First, power grid operator need choose a resilience metric, which match its expected aim and preference. Different resilience quantification metrics have their advantages and disadvantages and can be calculated by specific and executable system function equations. Then, power grid resilience can be quantified as a system function value at each moment. Thus, changes in resilience of the power grid can be expressed as changes in the value of the system function, which can be visually observed and utilized by the grid operator. A typical resilience curve is depicted in Figure 4. The whole resilience curve analyze progress can be divided into three main time states[8,14], namely pre-event, during and after event, and recovery.

Generally, the power grid operates in the state of normal condition, as well as pre-event state. In this period, the power grid operates in stable state. Thus, the system function value is stable and highest overall, which represents the resilience level under normal operation. Some anticipation methods can be utilized for predicting the potential damage[77], building power backup strategies[12], deploying various prevention technologies[78]. In addition, real-time monitoring the operational status of the grid[79] and utilizing other cutting-edge communication technologies are two key methods in this state[80].

When an extreme event occurs at t_1 in Figure 4, the power grid is possible to change to the damaged condition. During the disrupted event, some preparatory responses can keep the resilience of grid at stable level in a short time. Then, the power grid may suffer a resilience degradation after the event, as shown as the time period t_1—t_2. At the state of during and after event, the magnitude and speed of the degradation impact depends on the robustness[71], absorption[81], adaptability[82] and capacity of power grid[83]. In addition, the identification of critical components of power grid and the deployment of adaptive technologies in the power supply and demand sides are two main coping methods in this state, eliminating the negative impact as fast as possible. In the damaged condition at period t_2—t_3, the system function will keep a low value waiting for restoration actions.

The recovery state is the transition state of the power grid from its damaged condition to its stable condition, which starts from t_3 to t_6 in Figure4. The whole recovery progress consists of restoration and infrastructure recovery. Restoration action starts from t_3 to t_4, which will rebuild a certain portion of the performance of the power grid. There are two features in this state: (1) the maximum energy performance damaged (the difference between the target

Table 1 Examples of the adverse effects of different extreme events on urban power grid

Extreme events	Location	Date	Adverse effects
Heavy rain and waterlogging	Zhengzhou, China	2021.7.20	Urban waterlogging beyond the disaster prevention limit led to 292 deaths and 47 missing people and led to power outages and communication network failures within the city for nearly 7 days.
	Beijing, China	2012.7.21	Extraordinarily heavy rainfall caused urban flooding, resulting in 1.602 million people affected and economic losses of 11.64 billion yuan. One 110 kV substation was flooded and out of service, and 25 10 kV distribution lines had permanent failures.
High temperature and drought	Chengdu, China	2022.8	Due to the tight supply of water and electricity and high temperature, a large number of office areas, factories and residential areas have been cut off or limited.
Storms	Dallas, USA	2021.2.15	The extreme cold weather caused many winds power and natural gas-fired generators to shut down, resulting in the collapse of power grid and causing power outages in up to 4 million homes and affecting water for more than 10 million people.
Lightning strike	London, UK	2019.8.9	Affected by lightning strike, large gas-fired generators were disturbed and shut down, the system frequency dropped rapidly, and the low-frequency tolerance of wind turbines caused the turbines to go off-grid, further triggering low-frequency load shedding actions and affecting more than 1 million people with power outages.
Fire hazard	New York, USA	2019.7.13	The transformer fire caused a widespread power outage for more than 24 hours, resulting in the failure of traffic signals, the suspension of subway operations, and the paralysis of traffic, affecting more than 9 million people.
Cyber attacks	Kiev, Ukraine	2015.12.23	Ukraine's power grid was hit by a cyber-attack, causing a massive blackout in the capital city of Kiev, with power interruptions of 3-6h, affecting about 1.4 million people.
Military Operations	Ukraine	2022.9	Due to the Russian bombing, there was a large-scale power outage in six states in Ukraine, including Poltava, Sume, Kharkov, Dniporo, Odessa and Zaporoge.

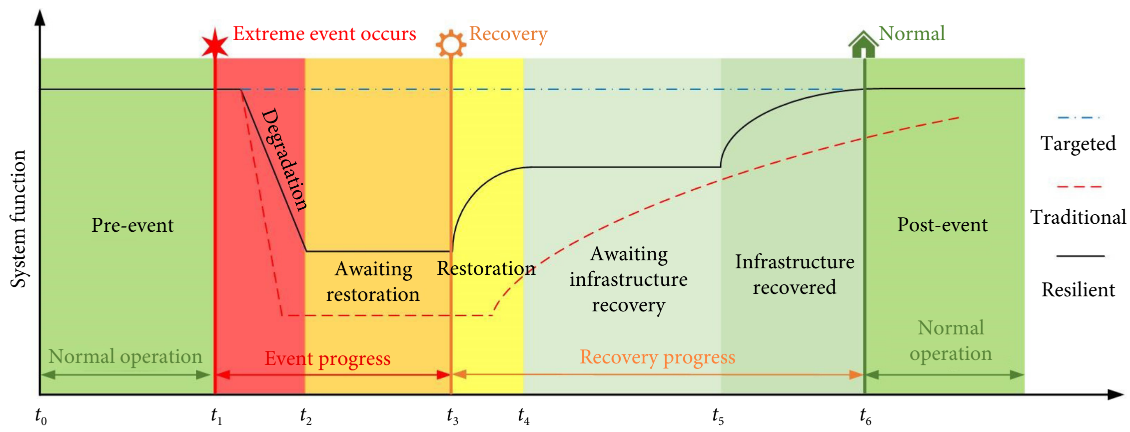

Fig. 4 Typical system function curve of resilient power grid.

and the minimum performance level), and (2) the time needed to return to the stable condition[84–86]. The effectiveness depends on the restoration resources of the power grid, including supply, demand, energy resource availability, storage, transportation system, and communication network support[87–89]. The restoration actions will make the resilience recover to a higher but still damaged level, awaiting further infrastructure recovery at t_4—t_5. After repair and reconstruction by the grid maintenance stuffs, the infrastructure of power grid will be fully restored to its capacity of energy supply and delivery, which may take a long time. The infrastructure recovery progress is shown as the time period t_5—t_6 in Figure 4. The time period after t_6 can be cosidered as post-event state, as well as the next pre-event state beginning.

2.2 Resilience quantification

Different resilience quantification assessment methods differs from resilience quantification metrics[90]. In this paper, the proposed metric is divided into four main categories, namely analytical matric, probabilistic metric, curve-based metric, and hybrid metric, which focus on different time states, features, and resilience indicators.

2.2.1 Curve-based metrics

A metric based on operability trajectory is introduced in ref. [91]. It is only used for the restoration, which can assess the resilience of grid at the time state of during and after event. A systematic resilience metric considering the social welfare is proposed in ref. [92] using a bi-stage stochastic framework for network restoration and planning. In the study, the social welfare curve is composed of sub-indices of resilience metric, including normalized robustness, recoverability, and rapidness. It is regarded as a generic index for different systems because it can assess the impact of repair crew shortage with normalized value. A tri-stage metric that consists of vulnerability metrics, degradation metrics, restoration efficiency metrics and microgrids resilience metric are proposed in ref. [93] to assess damage level, temporal degradation, restoration effects, and resilience of microgrids. It uses normalized value to reduce complexity, but it cannot capture preventive, post-degraded, infrastructural recovery, and adaptive resilience of the grid. Curve-based metrics are the mainstream to resilience quantification, by which operators can visualize the changes in the resilience level of the urban power grid. And many real-time response strategies can be developed based on curve-based metrics and in actual deployment.

2.2.2 Analytical metrics

Multiple indexes can be used to characterize power supply performance planning, design, management, and operation[94]. An analytical metric proposed in ref. [95] focus on the network topology, using six factors named algebraic connectivity, critical fraction, clustering coefficient, average path length, betweenness centrality, and graph diameter of the network. Take timely and proactive measures such as deploying distributed PV, energy storage systems and other distributed resources. In ref. [96], the resilience quantification progress is formulated as a multi-criteria decision-making problem using various parameters of network topology. However, it cannot assess the speed of recovery and the time required for supply restoration, which is of value for resilient grid.

In addition, metrics are defined to measure demand loss percent, generation margin, and transmission system adequacy during and after-event. And the metrics that accounts for quantifying efficiency and economic consumption of restoration progress are also proposed. Focusing connectivity and operational functionality of the power grid, assorted metrics are proposed in ref. [97]. The resilience metric in ref. [98] is defined as a ratio of energy storage failure rate during the extreme event to the critical demanded. However, the metric is not generic for resilience assessment outside of battery system, due to the lack of considering other infrastructure degradations. For restoration, an resilience metric for hybrid microgrids is proposed in ref. [99] to assess the demand response effects and the capability of power system. Analytical metrics contain various factors, which can match the operators' diverse demands and combine more information with specific objectives.

2.2.3 Probabilistic metrics

As the resilient operation of urban power grid has high uncertainties, probabilistic metrics are of importance to the resilience quantification assessment. Traditionally, Bayes formula based probabilistic metric can be utilized for this process. In addition, four key indices are proposed in ref. [100], which named the expected number of line outages, loss of load probability, EDNS, and difficulty level of grid recovery, to consider the impact of probabilistic line disruption on system resilience. A probabilistic resilience metric utilizing point estimation method is proposed to cope with the challenges of uncertainty in matching photovoltaic energy supply and users' demands[101] . Relatively speaking, current research on probabilistic metrics-based resilience assessment methods is lacking. However, the increasing uncertainty in urban power grid caused by more and more renewable energy and distributed resource should be quantified by advanced probabilistic metrics.

2.2.4 Hybrid metrics

A code-based metric is proposed in ref. [102] to assess the real-time resilience of urban power grid, considering the reliability index. However, it is unable to quantify and compare network resilience for longtime-last event. To the future energy resource structure changes and infrastructure development policies, transmission system resilience is evaluated by combining with adequacy index[103]. Bi-stage multiple metrics measuring supply and demand balance, microgrids deployment and renewable energy resources is defined in ref. [104]. However, the impact of deployment of distributed generation (DG) is not included, which is valued by urban distribution operators. In general, the hybrid metrics combines the advantages of different types of resilience assessment methods, which consider other concepts and characteristics of power grid operation assessment.

In summary, a uniform standard and all-inclusive resilience metric is lack in current research, as the demand is diverse and varied. Most of the resilience metrics concentrating on degradation and recovery progress against extreme events, while fewer reflect the preventive and adaptive capacity of the urban power grid[90]. A rational integrated resilience evaluation method should select different resilience metrics depending on the scenario. At different time states of an extreme event, all these metrics combinations should have been tested as possible to make a most matchable metric combination for actual demands. Resilience quantification metric chosen progress is the first step of achieving resilient operation of urban power grid, which should be consider carefully for operators and designer of a smart city.

3 Resilience enhancement strategies

Global climate change, economic recession, and regional conflicts have increased the frequency of extreme HILP events in nature and society, with even worse consequences for urban power grids. With the proposed urban power grid infrastructure resilience evaluation framework, operators have already visualized and understood the level of resilience of an urban power grid in multiple dimensions. Next, an ideal city urgently needs effective resilience enhancement strategies to ensure security of the urban power grid, which is the energy basic of urban infrastructure. There are various strategies that can enhance the resilience of urban power grid. This paper summarizes these strategies into six categories, including microgrids based strategies, active distribution networks-based strategies, integred and multi energy systems-based strategies, DERs and flexible resources-based strategies, cyber-physical systems defense methods to enhance resilience, and other specific resilience enhancement methods including probabilistic forecasting and analysis, AI driven methods, and other cutting-edge technologies, as shown in Figure 5.

3.1 Microgrids

Microgrids are smaller, decentralized, independent power systems, which is capable of self-control, protection, and management. It can be operated either with the external grid or in isolation, which can be considered small-scale power generation and distribution system. It brings distributed power sources, energy storage devices, energy conversion devices, associated loads and monitoring, and protection devices together and has highly flexibility. Thus, microgrids approaches are the most mainstream strategies to enhancing grid resilience in smart grid technology[105]. The capabilities of a microgrid to enhance the grid resilience include five main categories as follow[14].

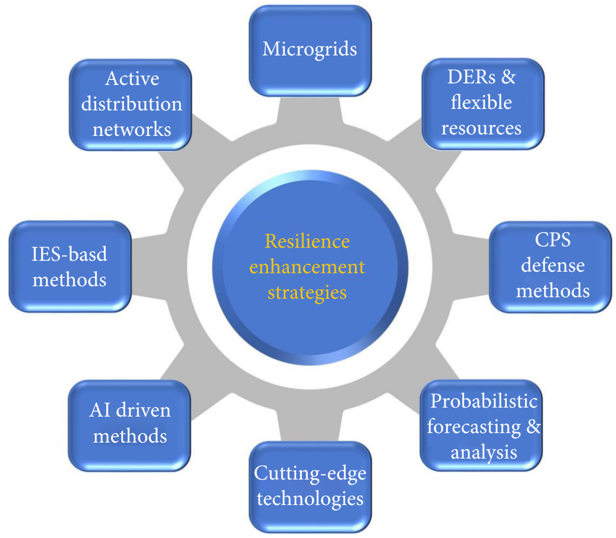

Fig. 5 Specific resilience enhancement strategies for urban power grid.

3.1.1 Converting grid to microgrids

A planner–attacker–defender model is adopted to determine the capacity and optimal location of power switches in ref. [106]. Through the combination of capacity expansion and switch installation, the power grid can ensure optimum resilience performance under attacks. In ref. [107], local distributed energy resources (DERs) and neighboring load centers are integrated to make the fast division of distribution network into community microgrids against an extreme event. Similarly, a distribution system reconfiguration method is proposed in ref. [108]. In addition, graph and network theories are used in ref. [109] to assess the effect of adding microgrids on the resilience of an interdependent gas-power network.

3.1.2 Dynamic microgrids deployment

A load shedding method for creating dynamic microgrids is proposed in ref. [110] to restore critical loads from the power outage. And an event-driven and service-oriented approach is described in ref. [111] to assess and rebuild better resilient grid partitions at run-time. Besides, an instant and dynamic reconfiguration method linking a cluster of microgrids together can significantly enhance the grid reliability and resilience[112]. For restorative process, a recovery scheme using master-slave method with microgrids[113] exploits benefits of operational flexibility to enable more critical load pickup.

3.1.3 Networked microgrids

During extreme events, many pre-connected microgrids can form a network to support each other to keep the continuous electricity supply, which are named networked microgrids. These microgrids can inter-exchange energy to achieve higher overall operational efficiency and lower risk of damaged. Networked microgrids can enhance the power grid resilience by flexible disconnecting/reconnecting strategies[114], sharing power and optimal planning[115]. A resilience-oriented optimization strategy is proposed in ref. [116] considering feasible islanding in normal condition for saving critical loads. Another operational method considers connecting neighboring microgrids to improve resilience[117]. In short, the future deployment of smart grid technologies, new business models, and involvement of new stakeholders enable networked microgrids to be an operational method to enhance grid resilience[118].

3.1.4 Multiple-microgrids

Comparing to networked microgrids research based on topology changing of many existing or dynamic microgrids, multiple-microgrids consist of microgrids and other different physical forms of energy systems, whose resilience enhancement problem always has diverse objectives. One direction of multiple-microgrids methods is based on make various interdependent microgrids a set to enhance the resilience of power grid[109]. The stochastic multi-objective framework with multiple-grids are widely studied in energy storage system[119], power-water distribution system[120] and urban plugin electric vehicle and renewable energy system (PEV-RES) interlink system[121]. In addition, a hybrid stochastic-interval operation strategy for multi-energy microgrids is proposed in ref. [122], in which adjustable operational strategies are determined to hedge uncertainty by considering operators' risk preferences. Another research direction focuses on the vulnerable equipment identifying in multiple-microgrids[123]. By addressing the vulnerability of multiple energy carrier microgrids against various interdictions, preventive reinforcements can increase the resilience of energy supply.

3.1.5 Other methods

Other microgrids-based methods also are proposed to cope with different challenges in various types of smart cities. To identify the sensitive loads in island mode, stability analysis[124] and economic analysis[125] are necessary. When destructive events occur, a bi-stage reserve scheduling-based framework can help the distribution system operator against resilience decreasing[126]. Comparing to other types of resilience enhancement methods, microgrid methods have a high possibility of implementation in real urban power grid and its effectiveness has been proven many times.

3.2 Active distribution networks

The active distribution networks (ADNs) also have been a vital research field of planning and operation of electric power grid. ADNs are an actively controlled and operationally capable distribution network. It contains multiple forms of distributed resources, including distributed generation, distributed energy storage, electric vehicle charging and switching facilities, and demand response resources. The core of ADNs is the conversion from passive consumption to active guidance and active utilization of distributed resources. These technologies can transform the traditional passive energy consumption distribution network to that can actively regulate and participate in the control of the urban power grid according to the actual operating state of a smart city. For dynamic resilience enhancement, a recursive optimization model based on Markov decision processes is developed in ref. [127] to make state-based actions for ADNs. By making full use of DG, ADNs make the distribution system become considerably resilient through planning-operation activities prior, during, and after an extreme event[128].

Meanwhile, high penetration of distributed renewable energy introduces significant uncertainties to ADNs. Optimal control methods accounting for inherent uncertainties are required to enhance the resilience of power grid by keeping voltage security of ADNs. A stochastic receding horizon control method is proposed in ref. [129],which can effectively enforce voltage regulation against uncertainties with the prescribed probability level. Besides, distributed control approaches are widely utilized in voltage control of ADNs to enhance the resilience of urban power grid. A strategy to ensure voltage security of ADNs with global sensitivities is proposed in ref. [130], which integrates network information from global optimization view to coordinate energy storages, PV inverters and the OLTC within little communication and computing time. In summary, ADNs make the urban power grid can active response extreme events to resilient operation, which is a thriving research direction with the development of intelligent sensing and control technologies.

3.3 Integrated and multi energy systems

Integrated energy systems (IES) and multi energy systems are new type of energy system that integrate a variety of energy sources such as electricity, natural gas, heating, cooling, water, and energy storage in a region. They can achieve coordinated planning, optimized operation, collaborative management, interactive response, and complementarity between multiple heterogeneous energy subsystems, effectively improving energy efficiency. They combine different forms of energy networks, whose resilient operation interacts with each other[20]. Meanwhile, multi energy systems form as other urban infrastructure networks such as transportation system become more electrified. Urban transportation system can enhance the resilience of distribution network. As the increasing proportion of urban electric vehicles (EV), EV aggregator would like to reduce the risk of high complexities and uncertainties[131]. Based on effective scheduling of EV aggregators, EV fleets with vehicle-to-grid tech can defense the random attacks for distribution network during and after the event occurs[62]. In restoration, an autonomous EV-assisted load restoration architecture is proposed to enhanced feeder-level resilience[132]. Besides, frequency regulation[133] and adaptive frequency response[134] of electrified railway also can be frequency support for keep the urban power grid resilient operation. Through line hardening and DG placement when outages occur, the distribution lines and traffic lights are more resilient with the coupled power distribution system and urban transportation system[135]. By optimizing multiple time sections of traffic flow with the power grid, the system adaptability increases by reducing incident response times significantly.

For integrated electricity and heat system, some novel models are proposed to reduce the mathematical complexity of the resilience enhancements strategies, including the flexibility evaluation method incorporating district heating networks[136] , the efficient robust scheduling model[18], and the convex heat and power dispatch model based on simplification, and constraint relaxations[137]. For integrated electricity and natural gas system, the non-isothermal model proposed in ref. [19] avoids the traditional isothermal assumptions and can improves the accuracy of resilience interaction assessment significantly.

3.4 DERs and flexible resources

With large-scale distributed energy resources (DERs) and flexible resources connected to the urban power grid, there is a high degree of flexibility at both the source and load ends. In a smart city, DERs and flexible resources include distributed energy source (e.g. distributed photovoltaic, distributed wind power, and fuel cells), energy storage devices (e.g. lithium batteries, super capacitors, flywheel energy storage, thermal storage, ice storage and cooling, hydrogen energy, and other types of new energy storage), flexible loads (e.g. electric vehicles, switching stations, dispatchable loads and other types of flexible loads), flexible prosumers (e.g. photovoltaic users, intelligent buildings, virtual power plants, and other types of energy producers, and consumers), flexible grid devices (e.g. intelligent soft switches, flexible switches, energy routers, solid-state transformers, new converters and other flexible and controllable intelligent equipment). It can be used to enhance the resilience of urban power grid through intelligent operating methods. Moreover, the cost of using DERs to support urban power grid resilience will be significantly less than the cost of infrastructure reconstruction in developed cities and that of infrastructure construction in developing cities.

There are many studies focusing on the rational use of DERs to support resilience of urban power grid. A framework which can enhance the recovery capability under extreme events for resilient distribution network to utilize all DERs is proposed in ref. [138]. In addition, an optimal dispatch model of repair crews and mobile emergency generators are proposed in ref. [139] to improve the restoration capabilities of existing DERs installed in the distribution systems. And a stochastic optimization method based on scenario probability is proposed to configure the photovoltaic and energy storage devices considering resilience enhancement against typhoon disaster[140]. DERs and flexible resources are the valuable during extreme events, but the lack of cross-regionality makes it is only one piece of the perfect solution that keep the whole urban power grid resilient in a disaster.

3.5 Cyber-physical systems

From the perspective of urban power grid, cyber-physical systems (CPS) are the integration of the physical power grid with communication network. Therefore, CPS aim to fully reflect the information and physical processes of urban power grid operation, reflecting the information-physical coupling mechanism and risk propagation mechanism. To ensure resilient urban power grid operation, CPS support global system optimization through more accurate control methods with cyber technologies, improving the efficiency of energy and equipment utilization under extreme events.

However, CPS have the high risk of cyber-attacks and cybersecurity and resilience of wide-area monitoring, protection, and control applications (WAMPAC) to CPS is summarized in ref. [2]. The CPS resilience can be divided into infrastructure layer attack resilience application layer attack resilience. To achieve WAMPAC, there are four specific steps: risk assessment, prevention, detection, and mitigation. The concept of holistic resilience cycle is introduced to improve CPS security of electrical power systems. For defense the potential false data injection (FDI) attacks[141], optimal coding schemes[142] can enhance the resilience of CPS. In restoration, various smart grid methods is summarized in ref. [143] to enhance CPS resilience. Furthermore, the exploitation of other urban components' behaviors to inform the design of the physical system and the cyber system to ultimately enhance the resilience of CPS is introduced in ref. [144]. CPS technologies is developing fast now, making the resilience enhancement of CPS in smart city more safe, efficient, and economical.

3.6 Other resilience enhancement methods

3.6.1 Probabilistic forecasting & analysis

With the percentage of renewable sources continues to increase in urban energy supply systems, the actual urban power grid resilient operation always has a high degree of uncertainty. Probabilistic forecasting is of important to cope with various uncertainty challenges during the entire time states of resilience analysis progress and probabilistic forecasting. Traditional forecasting methods in power systems take a single point value as the output result, which have ineradicable errors and cannot effectively quantify high uncertainty. Therefore, various forecasting methods have become effective means of dealing with such uncertainty problems in power systems. Unlike traditional point forecasting, probabilistic forecasting in power systems takes the probability distribution, quantile, and prediction interval of the forecast object as the output form, which can effectively quantify the forecast uncertainty. In addition, probabilistic analysis which focus on influence of extreme events, flexibility of DGs, volatility of renewable energy resources, and infrastructure maintenance fleets. Through digging out their uncertainty characteristics and analysis the coupling relationship, urban power grid operators can establish corresponding resilience resources allocation strategies.

Some reasonable combinations of probabilistic forecasting and analysis technologies form various probabilistic methods, which are proposed to enhance the resilience of urban power grid. A stochastic approach to modeling the outage time and duration and uncertainty in the load and solar resource forecast are consider in probabilistic resilience of DER systems[145]. Besides, a risk-based probabilistic resilience framework is proposed in ref. [146] to quantify the effects of smart operational measures. Meanwhile, infrastructure hardening solutions are detailed to improve the distribution system resilience. For prediction intervals, an cost-oriented machine learning framework is established in ref. [147] to bridge the gap between forecasting and decision. And a methodology to probabilistically assess the resilience of distribution network under different weather scenarios was presented in ref. [148], enhancing distribution grid resilience by considering other external factors such as urban traffic and vegetation. To quantify the uncertainty of wind power generation, an extreme learning machine based probabilistic forecasting method is proposed in ref. [149]. And an adaptive bilevel programming (ABP) model with extreme learning machine based quantile regression is developed in ref. [150], which show the significant effectiveness in anticipate process of resilience enhancement. By probabilistic forecasting and analysis technologies, the uncertainty during urban power grid resilient operation can be model as relatively certain and quantified mathematical problems, which significantly reduce the operational risk of a smart city.

3.6.2 AI driven methods

Artificial intelligence (AI) methods can compensate for the shortcomings of modeling-based grid resilience enhancement methods which depend on accurate parameters and system knowledge. Cause it is quite challenging for modern power grids with increasing dimensionality and complexity. Various advanced machine learning technologies are integrated with large amount of real-time data from wide area measurement systems and intelligent electronic devices to effectively enhance power grid resilience and ensure the reliable and secure operation of power grid[151]. A data-driven multi-agent framework using a deep reinforcement learning (DRL) algorithm is proposed to plan for the deployment of shunts to enhance power grid resilience against multiple line failures[152]. DRL framework also can be utilized to solve multi-microgrids formation problems[153]. A hierarchical and community-scale solution is developed to resolve crucial distribution grid issues arising from high-penetration PV and enhance grid reliability and resilience, which combines the AI, home energy management system and aggregator[154]. However, the effectiveness of current AI driven resilience enhancement methods in resilient power grid depends on the quality of historical data set from HILP extreme events. Thus, the high precision disaster simulation techniques are crucial because the high-quality historical data set of HILP extreme events is rare.

3.6.3 Other cutting-edge technologies

Oher cutting-edge technologies are also deployed to enhance the resilience of urban power grid. For instance, a soft open points-assisted method is proposed to enhance distribution network resilience against the potential cyber-attacks[155]. A self-organizing map based method is proposed to achieve resource allocation and operational dispatch, which can removes some of the disadvantages of subjective weight assignment methods[156]. Peer-to peer (P2P) energy trading method in distribution network[157,158] is utilized to manage the volatility of renewable energy generation, which can reduce the risk of uncertainty against extreme events. With increased battery capacity, improved safety technology and lower costs, the battery storage station[159] and wind-hydrogen storage[160] can enhance distribution grid resilience. In addition, mobile energy storage can by providing localized support to critical loads during an extreme event[161]. Its mobility provides operational flexibility to support geographically dispersed loads comparing to stationary storage. By combining a wide range of cross-disciplinary and cutting-edge technologies, the resilience enhancement methods become more and more flexible and effective against extreme events for urban power grid in a smart city.

4 Further development

Nowadays, global major cities have an increasingly well-developing and smart infrastructure, which make the citizens' future demand for a smart city more diverse and complex. However, the deterioration of the global climate and the intensification of geopolitical conflicts deepen the influence of HLIP extreme events on a smart city and how to achieve these goals is becoming a greater challenge. More and more future technologies can be used to ensure the resilient operation of urban power grid. This paper proposes six possible future further development directions, namely power-electronized urban distribution network, flexible distributed resource aggregation, cyber-physical-social systems, multi-energy systems, intelligent electrical transportation, and AI and big data technology as shown in Figure 6.

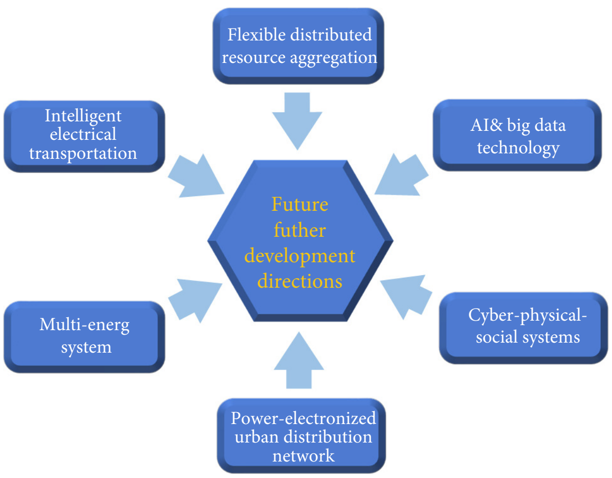

Fig. 6 Future further development research directions.

4.1 Power-electronized urban distribution network

With the vigorous promotion of the green and low carbon transformation of energy, the traditional urban power system dominated by the power generation is changing to the modern power grid dominated by the power electronic devices. A large amount of renewable energy resource is connected to the urban power grid through electronic devices, which will make the resilient power grid have obvious non-linear characteristics. The wide range of non-linear characteristics makes power-electronized devices more difficult to control when coping with extreme events, because its instability risk will be possible to superimpose double uncertainty of renewable energy resource outputs and damage level of extreme events. Meanwhile, massive flexible resources are connected to the distribution network through power electronic devices, and the resulting problems of keeping the urban power grid resilient under extreme events and coordinating control of source-grid-load-storage have become more prominent. Power electronic devices are the key future technologies to increase the energy delivery capability of urban distribution network, which can change power flow over designated routes and topology of distribution network. Thus, the interaction of the load, grid and generation will be changeable, which will threaten the existing resilient operation of urban power grid.

Based on more and more key power electronics devices such as flexible soft switches, power electronic transformers, and energy routers deployed in the urban power grid, a power-electronized urban distribution network gradually forms. It will provide interfaces for large-scale distributed power supplies, solving the problem of intermittent and fluctuating distributed power supplies and optimizing urban distribution network currents and power quality in the extreme condition. It will also enhance flexibility of urban power grid reconfiguration during emergency control and increase the speed and efficiency of grid recovery after a disaster. Combining with conventional control strategies of the power-electronized urban distribution network, it will increase resilience of the urban power grid against extreme events.

4.2 Flexible distributed resource aggregation

For the complex coupling of multiple uncertainties in urban power grid, safe and reliable flexible distributed resource aggregation has been an important direction of power grid resilience. Future aggregation technologies for modern urban distribution grids are required to make the massive flexibility resources be measured and mobilized. When extreme event occurs, flexibility resources can automatically and timely become an adequate adjustable resource to the damaged distribution networks, which will be a key resilience enhancement technological solution for the urban power grid. In the direction of future flexibility resource aggregation, the aggregation and coordinated optimization of distributed energy resources such as distributed generators, energy storage systems, controllable loads and electric vehicles will be realized through advanced information and communication technologies and software systems. A virtual power plants with power supply coordination and management functions and participation in grid operation will be established, which will provide a more adequate prevention resource and auxiliary services for resilient urban power grid.

Moreover, decentralized approaches have become a new research hotspot to aggregating flexibility resources. Decentralized resource aggregation approaches will often use decentralized computing, eliminating the need for a central authority to manage and allocate resources, which will expand the range of resources that can be aggregated and encompass a wider variety of distributed resources. Moreover, resources are aggregated and optimized spontaneously by users in the network, thus the economic and time costs of the transaction and resource aggregation process will be reduced. It is important when defending against extreme events, where the time saved can increase the resilience of urban power grid. The development of various peer-to-peer (P2P), blockchain and smart contract technologies can significantly reduce the cost and decrease the response time of flexibility resource aggregation, which can be utilized to compensate for the shortcomings of traditional aggregation methods. In summary, centralized or decentralized distributed resource aggregation approach will effectively improve the resilience level of the urban power grid before, during and after extreme events.

4.3 Cyber-physical-social systems

Cyber-physical-social systems (CPSS) are the extension of cyber-physical systems (CPS), which integrate cyber systems, physical systems, and social systems. CPSS promote information and energy resource from a single dimension to three dimensions, which will include more urban infrastructure operators in a smart city. Meanwhile, more and more unexpected social crisis occurs in a modern city, which will challenge the urban resilient operation under the citizen's wonderful vision of a smart city. The lockdown caused by various epidemics, the energy price skyrocketing due to regional conflicts, and tensions spread by social networks are no doubts that hurt urban infrastructure actual defense capacity facing extreme events. From the perspective of resilient urban power grid, the influence of social system is often ignored in traditional studies. In contrast to natural disasters, extreme events in the social sphere can also cause large-scale power outages in the grid. For example, the spread of rumors of natural disasters on mobile social media is potential to trigger public transport overloads and reduce the resilience restoration action of the grid. Therefore, it is important to model and assess the behaviors of various agents in the social system.

Conversely, rational methods of dispatching energy at the societal level can be of importance for the whole CPSS in a smart city, such as considering stochastic gaming, blockchain technology, and other smart energy trading strategies. They can not only enhance the resilience of the power grid for a smart city from the physical systems through optimizing energy delivery capacity but also decrease the risk of the urban infrastructure network collapse under malicious cyber-attacks. Thus, the resilient enhancement methods of power grid under CPSS vision should be extensive researched by academia and industry to achieve the more complex goals of a smart city in the future.

4.4 Multi-energy systems

In the future, smart cities will be more complex with multiple energy coupling and will combine multiple forms of microgrid development. In addition to the coupling of complex energy supply networks such as electricity, heat, cooling, and natural gas deepening, some new forms of energy delivery network such as hydrogen network. Meanwhile, the energy supply infrastructure contained within the urban buildings also becomes complex. Some mutually supportive communities can be formed under extreme events through flexible multi-energy aggregators, in which various energy demands of citizens can be satisfied.

As the coupling relationship between multi-energy flows and power grid is not fully adequately studied, the potential risk and stability against extreme events of multi energy system should be carefully assessed. Most of the existing studies have only developed planning models from a single or two dimensions for normal condition, such as economic or environmental, without taking the diversity and expandability of the objectives of multi-energy coupled systems into account under extreme events. And the necessary consideration of effective and quantitive requirements assessment methods in emergency situations for energy consume terminals and end users are lack. In addition, to address the coupled uncertainty of complex multi-energy systems, most of the existing studies utilize robust optimization based on the worst-case scenario or stochastic optimization based on probabilistic scenarios. However, the historical data set for extreme scenarios of multi-energy systems is usually incomplete or missing, because the resilience research focus on HLIP extreme events which pose a most terrible challenge to resilient urban power grid. Besides, cities with different geographical characteristics and energy endowments will have varied multi-energy system structures. Combing local development plan and engineering feasibility, the interconversion flexibility of multi-energy systems can be fully used through smart and reasonable operating strategies to enhance resilience of urban power grid.

4.5 Intelligent electrical transportation

With the modern urban transportation system becoming more intelligent and electrical, there will be more and more intelligent transportation-based solutions to support resilient power grid, such as automatic mobile energy storage fleet, high-speed mobile emergency repair fleet, advanced forms of mobile energy carriers, etc. These transport fleets with disaster response and repair functions can directly increase the resilience level of the urban power grid during and after a disaster. The key to future research is how to allocate them most efficiently when they all have some degree of intelligence. Also, through flexible V2G and thriving autonomous driving technologies, shared autonomous electrical vehicle can be a resilience enhancement strategy. It will make full use of each individual's tiny mobile energy storage unit in the city, to achieve macroscopic disasters defense goals.

In addition, the electrification and intelligence of public transport systems are enabling the accelerated movement of people and materials in urban areas, including future electric high-speed rail systems, urban electric metro systems, electric logistics systems, and electric bus systems. It also makes the electric energy flow more complex and large-scale. Under extreme events occurring, various forms of energy storage in the electrical public transportation systems will be valuable emergency resources to support the resilient operation of urban power grid and restoration process of damaged urban infrastructure systems. To summarize, an integrated smart city infrastructure control framework and system needs to be established under extreme events, somewhere it is named a smart city brain. An ideal smart city brain must include electricity network, transportation system and other urban infrastructure systems, which should full consider the complex coupling relationship between these urban infrastructure networks and achieve most resilient operation status. Among them, there is no doubt that a modern resilient urban power grid has the priority to be protected and restored, by which the city can keep fundamental functions out of chaos. Based on the decision making through the smart city brain, a smart city operator can real-time optimize existing emergency response strategies under extreme events, ensuring the rational distribution of emergency personnel, tools, vehicles, and energy to achieve the predetermined resilient operation.

4.6 AI and big data technology

As the proportion of renewable energy supply in urban distribution grids increases, the risk of uncertainty in the resilient operation of urban grids will continue to grow. Massive measurement data and high complexity of future power system will pose a new challenge to AI and big data technology. Thus, it's necessary to analyze the spatio-temporal characteristics of multivariate heterogeneous distributed resources including storage, heat, cooling, gas, water, transportation, and other multiple users in the infrastructure network of a future smart city. Then the researchers can establish an effective and simple feature modelling method to quantify the resource response potential. Combining the dynamic aggregation method of distributed resources and mining the key features of multivariate correlation variables, some effective AI-driven prediction model can be constructed for massive distributed resources in the future. With the rapid development of AI and big data technology, there will be more data-driven solutions for predicting operational risk through historical data sets.

However, AI-driven methods have the disadvantage of unstable and uninterpretable. It will lead to the unsuitability of traditional AI-driven methods in resilient urban power grid operation scenarios with high load security requirements. In contrast, traditional model-driven methods have the advantage of high accuracy and interpretability, which can compensate the shortcomings of traditional AI-driven modeling methods. Therefore, the future efforts would be paid on developing AI-Modeling hybrid driven methods to assess and enhance the urban power grid resilience. In addition, the cloud-based hyper-converged architecture is needed for urban power grid resilience enhancement to achieve real-time AI data processing capabilities. Combing with edge computing, it can maximize the value of cloud and edge computing applications and meet the needs of various resilient urban power grid scenarios through a tightly synergistic approach, which will strengthen intelligent and secure big data storage and analysis for future smart city operation.

5 Conclusions

This paper makes a systematical review on the development of resilient power grid for smart city. Firstly, this paper divides the HILP extreme events that have impacts on resilient power grid into three categories extreme weather and natural disaster, human-made malicious attacks, and other black swan events. Secondly, resilience evaluation frameworks consist of resilience curve and quantification metrics are reviewed. Then, this paper summaries some types of proposed resilience enhancement strategies and methods. They are categorized as microgrids, active distribution networks, integrated and multi energy systems, distributed energy resources and flexible resources, defense in cyber-physical systems, and other resilience enhancement methods including probabilistic forecasting and analysis, artificial intelligence driven methods and other cutting-edge technologies. Finally, this paper proposed some potential future further research directions for some critical and creative discussion, including power-electronized urban distribution network, flexible distributed resource aggregation, cyber-physical-social systems, multi-energy systems, intelligent electrical transportation and artificial intelligence and Big Data technology. In conclusion, it is executable and possible to assess and enhance the resilience of urban power grid through diverse and flexible methods, which will effectively ensure safety of a smart city.

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Declaration of competing interest

The authors have no competing interests to declare that are relevant to the content of this article.

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