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Climate change adaptation with energy resilience in energy districts—a state-of-the-art review

Yuekuan Zhou [a,b,c,d]*

[a]*Sustainable Energy and Environment Thrust, Function Hub, The Hong Kong University of Science and Technology (Guangzhou), Nansha, Guangzhou, 511400, Guangdong, China*

[b]*Department of Mechanical and Aerospace Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong SAR, China*

[c]*HKUST Shenzhen-Hong Kong Collaborative Innovation Research Institute, Futian, Shenzhen*

[d]*Division of Emerging Interdisciplinary Areas, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong SAR, China*

Abstract

Energy efficiency, flexibility, and robustness can promote system sustainability and decarbonization under low-impact and high-probability events, whereas energy resilience is significant to survive power systems when suffering from high-impact and low-probability events. However, energy resilience is at its pregnancy stage with inconsistency in multiple perspectives, ranging from concept definition to quantification approach. Moreover, the consideration of energy resilience will conflict with energy efficiency, calling for the necessity on trade-off solutions. In this study, in order to ensure the survivability of district power systems when suffering from extreme events, an up-to-date review on concept definition and quantification approach of energy resilience was conducted, together with distinguished boundary and correlation with reliability, robustness, and flexibility in multi-energy systems. Recent advancement in distributed renewable systems, electric vehicles, peer-to-peer energy sharing, electrification and hydrogenation in power systems was provided, together with their potential contributions in future smart energy systems. By enabling each agent to become a power supply agent, a typology transformation from centralized to distributed energy prosumers was proposed, with an intermediate step-by-step transition from centralized power plants to distributed energy prosumers. Afterwards, multi-scale applications and future prospects of energy resilience are provided, including resilient heating/cooling of buildings, dynamical downscaling for robust design on urban morphology, mobility-based interactive energy sharing in regional districts, and smart microgrids with V2X (vehicle-to-everything) and energy flexible buildings. This study can highlight the significance in district energy resilience with joint and continuous endeavors and tradeoff solutions, during energy planning, design and operation stages.

Keywords: Energy Resilience; Energy Robustness; District Energy Systems; Climate Adaptation; Decarbonisation; Electrification and Hydrogenation

Nomenclature		MEG	micro energy grid
Abbreviations		OPM	Operation Oriented Preventive Measures
B2G	building-to-grid	OCM	Operation Oriented Corrective Measures
CCUS	carbon capture, utilization, and storage	ORM	Operation Oriented Restorative Measures
ECI	energy cost increase	PPM	Planning Oriented Preventive Measures
ECE	equivalent CO_2 emission	PCM	Planning Oriented Corrective Measures

*Corresponding author: Tel.:

Email: yuekuanzhou@ust.hk; yuekuan.zhou@outlook.com (Zhou Y.)

G2B	grid-to-building	PRM	Planning Oriented Restorative Measures
HILP	high-impact and low-probability	RC	resilience cost
HVAC	Heating, ventilation and air-conditioning	REe	renewable electricity
HRC	holistic resilience cycle	RAW	Risk achievement worth
IC	import cost	V2X	Vehicle-to-Everything
ICT	Information & Communication Technology		

1. Introduction

Along with the development of human civilization, traditional fossil fuels (e.g., natural gas, coals and fuels) play irreplaceable roles in energy supply with high stability. Over the past several decades, the economic prosperity in human society is at the sacrifice of traditional fuel consumption and environmental pollution. The energy shortage crisis and environmental issues become more obvious, especially with the ever-prospering prospects and ever-increasing energy consumptions at current stages. In the following-up several decades in 2050 or 2060, countries or regions all over the world call for the necessity on carbon-neutrality transitions. Carbon-neutral fuels, nuclear energy, and fossil fuels are promising candidates for the carbon neutrality transition [1]. The embodied emission in producing carbon-intensive structural materials (e.g., steel and cement) calls for carbon-negative strategies. Resorting to renewable energy with cleaner power productions gradually becomes the mainstream and attracts worldwide attention, to partially replace traditional fossil fuels. Considering instability and uncontrollability of renewable energy, stochastic and ever-increasing characteristics of energy demands, intrinsic characteristics of district energy systems need to be evaluated, especially for energy efficiency and energy resilience during normal and extreme events periods.

Civilization and advancement levels of a society are dependent on the capability in energy manipulation, control and utilization. With respect to energy consumption in end-users, building and transportation sectors consume around 30% and 20% of global energy, together with aggregated 35 billion tCO_2 worldwide. Renewable deployment, energy-saving, waste-to-energy conversion, carbon capture, utilization, and storage (CCUS) are effective strategies with potentials at 20%, 22%, 30% and 28% for carbon neutrality transitions, respectively. Renewable-powered electrosynthesis [2] can achieve a negative carbon footprint, by converting waste emissions into alcohols, oxygenates, synthesis gas (syngas), and olefins. Electrification and hydrogenation transformation in energy use can contribute to 30% decarbonisation in 2060 [3]. However, the high initial cost and low energy conversion efficiency highly restrain their further widespread applications. Furthermore, energy security and energy resilience need to be in line with the carbon neutrality transition roadmap.

During the normal period, the carbon neutrality transition roadmap highlights energy supply reliability, energy efficiency, and energy security (such as high-pressure H_2 storages) in energy conversion and storage, and energy flexibility in end-users, as summarized in Table 1. In terms of energy supply, the transition from traditional centralized energy systems (like central power plants, solar/wind farms, central controllers and etc) towards distributed energy systems (like BIPVs, decentral controllers and so on) shows overwhelming advantages in avoiding energy transmission losses [4], fast and immediate demand responses [5], flexible ownership among investors and high participation willingness [6]. However, the global climate changes will obviously affect the PV power output [7]. Furthermore, the decentralized energy supply system can incentive peer-to-peer energy trading and release energy/carbon trading rights to each agent (like trading mode and dynamic energy/carbon pricing). In terms of energy conversion and storage, energy efficiency and energy security have been widely studied, like energy security in high-pressure hydrogen tanks [8] and electrochemical battery charging/discharging processes [9], energy efficiency in solar-to-power [10], thermal-to-power [11], hydrogen-to-power conversions [12]. Hydrogen energy and economy play significant roles in seasonal balance, whereas storage and transmission become the most challenging issues [13]. Researchers mainly focused on hydrogen storage in gaseous forms, like reversible chemical reactions [14], physisorption of hydrogen on microporous adsorbents [15], carbon nanostructures [16], metal-organic frameworks [17][18][19], molecular compounds [20], novel organometallic buckyballs [177][21], sonicated carbon materials [22], and so on. However, H_2 storage in gaseous forms will occupy large volumes, leading to a low volume density.

Due to random and systematic errors of testing devices, the uncertainty of testing variables should be considered. Energy robustness is therefore widely applied when planning, designing, and optimizing multi-energy systems. Gabrielli et al. [23] conducted uncertainty-based robust design on a multi-energy system, with minimum computational complexity. Wang et al. [24] studied robust optimization on an integrated building energy system using a two-stage stochastic programming. The multi-objective optimization with Shannon-entropy-based decision-making shows relatively low total cost and carbon emissions, with 8.81% probability of failure. Moretti et al. [25] conducted robust optimization on energy component constitution and energy dispatch in multi-energy systems, considering the uncertainty of energy supply and energy demand. Results showed that, compared to the conventional deterministic method, the robust approach can ensure energy reliability with reserve margins.

In addition to normal periods, energy resilience has also been studied during extreme events, like extreme weather conditions and human wars. As summarized in Table 1, energy resilience for various scales of energy systems has been studied, including sensitivity analysis [26], the trade-off between energy efficiency and heat resiliency [27][28], time-duration for survival during power outage period [30]. From a small-scale perspective of a single building, Baniassadi et al. [27] studied energy efficiency and heat resilience of phase change materials (PCMs) in residential buildings. Results showed that the optimal solution on heat resiliency can lead to 60% energy savings. In respect to a building community, Shandiz et al. [29] conducted energy master planning on a residential community, comprehensively considering engineering, operational, and community resilience. The urban resilience for more than 1500 city buildings with 1971 snowstorms has also been studied [30], and the proposed approach can survive a three-day power outage.

Table 1. Summary of multi-criteria energy performance during normal and extreme events period.

Periods	Phases/Scales	Studies	Systems	Indicators	Results
Normal period	Energy supply	Lu et al. [31]	renewable energy in buildings	Energy robustness, energy mismatch, cost and CO_2 emissions	building loads prioritize other variables in combined objective
		Morstyn et al. [32]	Distributed solar PVs and peer-to-peer energy-trading	Operational cost	Self-organized prosumer with P2P energy sharing and trading can incentivize prosumers' participation willingness.
	Energy conversion and storage	Mohamed and Kamil [33]	PEM fuel cell	Energy efficiency, stack power and waste heat utilization	The waste heat recovery can improve the maximum stack power by 8%-10%.
		Zhou et al. [34]	A neighborhood building with integrated electric vehicles	Battery relative capacity	Grid-responsive strategy can slow down the degradation.
		Petkov et al. [35]	Storage with power-to-hydrogen	carbon emission and cost	90% decrease in emission
	Energy use	Zhou and Cao [36]	Distributed BIPVs, buildings and electric vehicles	Energy flexibility	Energy flexibility of integrated systems is highly dependent on energy controls.
		Zhou and Zheng [37]	BIPV and building energy systems	Energy flexibility and peak power from grid	The demand-side flexibility can reduce grid import power from 500.3 to 195 kW.
		He et al. [38]	A residential community with hydrogen energy	hydrogen consumption, grid power and energy cost	Annual hydrogen consumption and energy cost can be reduced.
Extreme events period	Single building	Baniassadi et al. [26]	passive survivability of buildings	thresholds of indoor climate	Energy codes subject to climate-sensitive energy resiliency.
		Baniassadi et al. [27]	PCM in residential buildings	energy efficiency and heat resiliency	Optimal solution on heat resiliency can lead to 60% energy savings.
		Kwok et al.[39]	Passive design on buildings	time-duration of overheating	The cross-shaped building form can be energy-efficient in responding to climate change.
		Sun et al. [28]	a nursing home	energy saving and thermal resilience	Both energy saving and resilience to extreme weather need to be considered in building design or retrofit.

	Building community	Pantua et al. [40]	Rooftop PVs	tilted angle of roof, solar power generation and structural resiliency	The tradeoff design is 26.5 pitch roof to balance the energy generation and typhoon resilience
		Shandiz et al. [29]	energy planning of communities	energy resilience metrics	Energy resilience of the community can be enhanced, including engineering, operational and community resilience
	Energy districts and grid	Katal et al. [30]	more than 1500 city buildings with 1971 snowstorm	urban resilience	Energy resilience can survive against the three-day power outage.
		Hossain et al. [41]	National Power grid	resilience risk factor, grid infrastructure density	Grid resilience and reliability are applied for US map categorization.
		Hussain et al. [42]	Microgrids for multi-energy systems	Response time, event occurrence and clearance times	Micrograids can provide energy resilience to multi-energy systems.

In order to characterize dynamic performance behaviours and take immediate response against extreme conditions, tools development for data synthesis on typical and extreme weather and advanced simulation platform have attracted researchers' interest. Nik et al. [43] developed a data synthesis approach out of the regional climate to quantify climate change on building energy performance. The proposed method can provide useful tools for simulations and performance prediction on future climate scenarios. Katal et al. [30] developed an integrated City Fast Fluid Dynamic and City Building Energy Model for multi-scale building energy simulation. The simulation platform can provide predictions on thermal load, microclimate condition, and energy behavior with high resolution. Zhang et al. [44] comprehensively reviewed modelling and control strategies on energy resilience of power systems. Melendez et al. [45] provided future directions on modelling community resilience with static and dynamic computational models.

With respect to countermeasures for energy resilience enhancement, researchers mainly focused on energy planning (e.g., renewable energy, power transmission, and backup source), resilience-based response (e.g., alternative energy and subsystem isolation), and restoration (e.g., enhancement in power distribution, decentralized energy supply unit, distributed energy prosumers, and so on). City-integrated renewable energy [46] with the integration of transportations for spatiotemporal energy migration can improve the reliability of local power energy systems [47], under extreme climate conditions. In addition, climate policies with energy independence and self-sufficiency can decarbonize the power system and ensure energy security [48]. Synergies within building, industrial and ecological boundaries can promote the rapid energy transition [49]. Based on above-mentioned literature review, several scientific gaps can be noticed:

1) there is no universally acknowledged method on energy reliability, robustness, resilience, and flexibility, with respect to concept definition, quantification, and interconnected relationship. Roles of energy resilience and energy efficiency in carbon neutrality transition have not been effectively identified yet. Contradictions between energy resilience and efficiency have not been effectively addressed, through energy system planning, operating, and optimization.
2) multi-dimensional approaches for resilience enhancement have not been proposed, considering different types of threat sources, energy recovery mechanisms, and phase-dependent defense measures (e.g., resilience-based planning, resilience-based response, and resilience-based restoration).
3) district energy systems during normal periods are mainly concentrating on energy efficiency, energy robustness, and energy flexibility, whereas energy resilience has not been well considered or even ignored in planning, design, and operation stages in district energy communities, leading to system fragility and vulnerability. Applications of energy resilience in district community planning are not clear for climate change mitigation and adaption.

The originality of the presented work is summarized below:

1) clear boundary on reliability, robustness, resilience, and flexibility is provided, in terms of concept definition, quantification, and interconnected relationship in multi-energy systems
2) an in-depth analysis is conducted on various types of threat sources, system recovery mechanisms, and phase-dependent defense measures to enhance energy resilience.
3) integration of energy resilience in planning, design, and operation stages of district communities is provided, to achieve the trade-off among energy efficiency, energy robustness, and energy flexibility. A clear roadmap for future decarbonization of district energy communities is provided, together with consideration on energy resilience under extreme events, like climate change, heat wave and

military wars.

In this study, methodology is introduced in Section 2. Section 3 provides concept definition, quantification approach, and interconnected relationship among energy reliability, robustness, resilience, and flexibility. Section 4 provides systematic approaches for energy resilience enhancement. Afterwards, applications of energy resilience in design, operation, and planning of district energy communities are provided in Section 5. Section 6 provides research outlook and recommendations. Last but not the least, research conclusions are drawn in Section 7.

2. Methodology

Just like the human body for surviving through infections or trauma, resilience management on integrated multi-energy systems is significant to address system complexity and uncertainty under climate change, extreme weather condition and future threats [50]. In this study, an overview on energy resilience was conducted in smart district energy systems, as demonstrated in Fig. 1. Firstly, concept definition and quantification approach on energy resilience are reviewed, together with fundamental roles and relationships among reliability, robustness, and flexibility. Afterwards, different types of threat sources, underlying mechanisms on resilience-based recovery, and technical strategies are introduced to enhance energy resilience. Thereafter, applications of energy resilience are introduced in building energy systems, integrating mobile electric vehicle systems, renewable systems and local microgrids. Last but not the least, in order to provide future research directions, research outlooks and recommendations are provided, with respect to a generic energy resilience quantification approach, energy resilience under extreme events, energy efficiency during normal operation periods, regional energy resilience, and stakeholders' participation willingness.

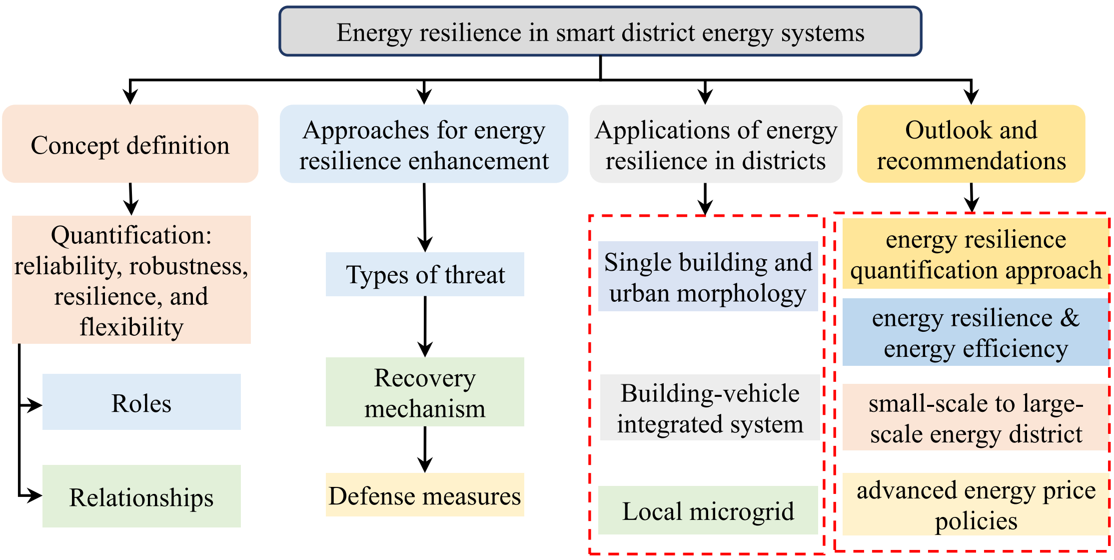


Fig. 1. An overview on energy resilience in smart district energy systems.

3. Concept definition and quantification approach on smart district energy systems

3.1. Concept definition

The national growth of rated capacity in renewable energy follows S-curves [51], whereas the disruption from weather-driven threats and cyber threats will lead to the fragility and failure of energy systems. In order to supply renewable energy with large quantities and high reliability, energy security, reliability, flexibility, and resilience were studied, in terms of concept definition, quantification methods, and technical strategies for performance enhancement. In this section, the concept definition is given to clarify the boundary between each terminology.

Energy Security: uninterrupted availability of energy sources at an affordable price [52].

Reliability: high degree of confidence for demand coverage. Several critical elements are required, including well-functioning electricity spot and mature contract markets, reliable transmission/distribution networks, and a secure state to withstand disruptions to reach equilibrium.

Robustness: flexibility that enables the system to function properly even when the structure is broken or damaged [53].

Flexibility: ability to manage onsite generation and energy demand based on local climate conditions, user needs, and grid requirements [54].

Resilience: the ability of the system to survive under strong and unexpected disruptions and to recover quickly afterward [55][56][57].

3.2. Quantification approaches and methodologies

3.2.1. Energy security

In terms of quantification approaches on energy security, a series of methods have been proposed in different dimensions [58], regional and national energy structures [59]. Ofosu-Peasah et al. [60] provide a holistic view on energy security, instead of a specific element, including investment, energy demand-side management, security and governance. Bompard et al. [61] proposed an approach to quantify the energy supply risk and explored associated mitigation strategies, considering both internal (national energy infrastructures) and external (energy supply from abroad) disturbances. By applying the proposed approach, the energy security of the Italy can be ensured. Gracceva and Zeniewski [62] quantified energy security with five systemic properties (stability, flexibility, adequacy, resilience and robustness). Kruyt et al. [58] evaluated energy security in four dimensions: availability, affordability, accessibility, and acceptability. Demski et al. [63] indicated that the affordability, vulnerability and reliability of energy determine the energy security in Europe. Abdullah et al. [64] assessed the energy security in Pakistan, from aspects of “Availability”, “Affordability”, “Technology”, “Governance”, and “Environment”. Results showed that, the weighted score of Pakistan's energy security decreases from 8.36 in 1991 to 7.59 in 1999, and then increases to 8.29 in 2018.

Approaches for energy security enhancement can be classified into independency on energy imports and regulation of economic and human well-being on affordability, vulnerability and reliability. Furthermore, inspired by bio-inspired diversity to prevent the spread of diseases, diversification and synergy in energy systems can improve the energy security [65]. Augutis et al. [59] applied different approaches for energy security forecasting, making preparations for innovative national energy strategies of the country. Sovacool and Mukherjee [66] proposed a synthesized approach to evaluate energy security. Islam et al. [67] assessed national energy supply security in Bangladesh. They concluded that, dependence on imported fossil fuel energy resources is full of insecurity, whereas renewable energy is promising as an alternative for fossil fuels. High-efficient utilization on local abundant renewable resources in Hawaii is critical to replace the crude import oil and achieve the energy self-sufficiency [68].

3.2.2. Reliability

Reliability indices of distributed systems mainly include failure frequency, mean failure times, mean time between failure and energy not supplied [69]. Modeling for power grid reliability is based on “two-state” model [70], and “three-state” version [71], in which meteorological parameters are classified into two (normal and adverse) or three types (normal, adverse, and major disaster). Stochastic transition between different types is modelled as a homogeneous Poisson process. Cadini et al. [72] studied power grid reliability, by integrating uncertain weather conditions with a cascading failure model through a customized sequential Monte Carlo scheme.

In terms of reliability quantification, Risk achievement worth (RAW) [73] is applied to evaluate the risk and component importance, as shown below:

$$RAW_{(i)}=\frac{1\text{-}R_s(Q_i=1)}{1\text{-}R_s}$$

where i is the component in the whole system, ranging from 1, 2,…, n. $R_s(Q_i=1)$ is the system reliability, when component (line) i has failed while R_s is the reliability of the original system.

Strategies for energy reliability enhancement mainly include renewable-energy storage integration with smart grid communication and control network [74], EV integration [75], fair electricity market [76], peer-to-peer energy sharing [77], and so on. Jafari et al. [76] explored a fair electricity market strategy to improve economic profits, customers' satisfaction, and microgrid reliability. Bayat et al. [77] studied both networked and individual operation modes to enhance energy reliability during emergency periods. Furthermore, the incorporation of energy reliability into economic, environmental and risk performances has been studied through weighted optimization for optimal design on renewable systems [78].

3.2.3. Robustness

Carpinelli et al. [79] comparatively studied critical distance method and the fault position method to improve the robustness of electrical power systems. Gabrielli et al. [23] conducted uncertainty-based robust optimal design to minimize total annual costs and CO_2 emissions, with enhanced robustness. The deterministic optimization can realise the minimum computation complexity, whereas the bi-objective optimization result on annual cost and robustness shows a slightly higher CO_2 emission. Lu et al. [80] studied uncertainty-based robust optimization and concluded that, stochastic optimization showed limited improvement in robustness, whereas the decrease in uncertainty degree of input parameters is more effective. Picard et al. [81] quantitatively studied the impact of occupant behavior on energy performance robustness of a zero-energy home. Results showed that the climate change will increase the energy consumption by 15%. Furthermore, compared to weather or climate change, the occupant behavior shows more obvious impact.

3.2.4. Flexibility

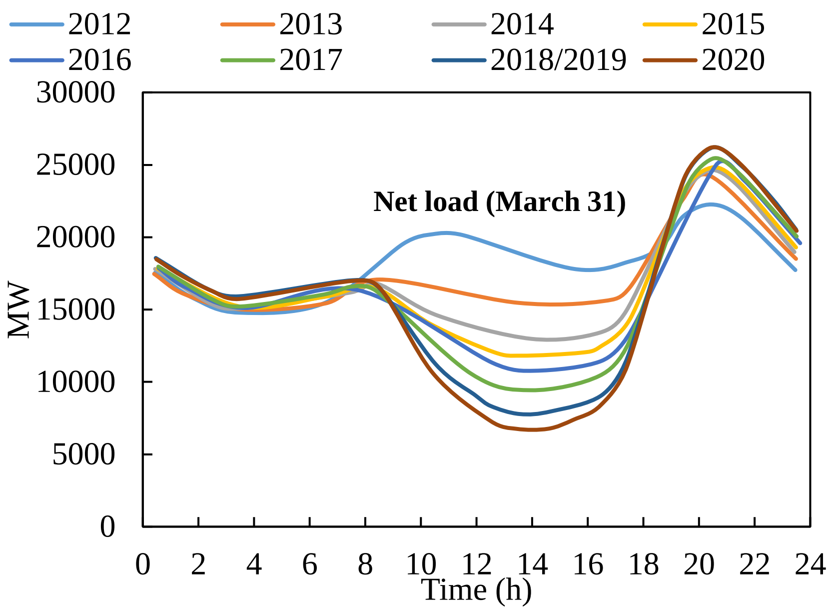


Fig. 2. Duck curve of California from 2012 to 2020 [82].

Due to the intermittence and fluctuation of renewable energy, and stochasticity in energy demands, the interconnection among buildings, renewable and power grid with low renewable penetration will lead to grid instability. To dynamically characterize the performance, the duck curve with the subtraction of electrical demand by renewable power, as shown in Fig. 2, can provide guidelines on design of both renewable energy and demand-side management. As demonstrated in Fig. 2, due to the annual increase in installed rated PV capacity, the duck curve gradually decreases at daytime. In order to improve the energy matching between renewable energy generation and energy demands, energy flexibility strategies can be proposed, through demand-side management [83] and regulation of power supply [84].

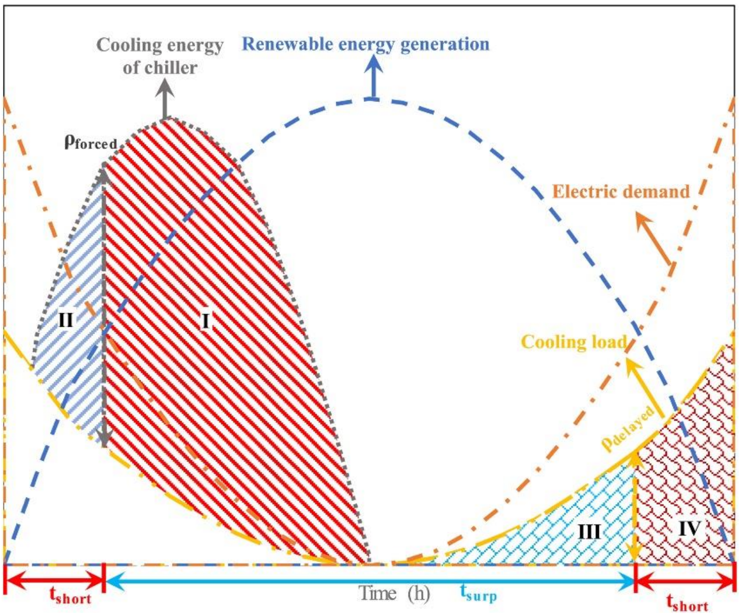


Fig. 3. Demonstration of the demand-side energy flexibility of renewable integrated cooling systems [5].

Generally, researchers focused on energy flexibility enhancement via demand-side management and power plants. Demand-side flexibility refers to proportion of demands that can be reduced, increased or shifted within a specific time-duration, so as to improve the variable renewable integration [85]. As demonstrated in Fig. 3, the discrepancy between renewable energy supply and electric demand requires the enforcement or delay of chiller operations, leading to forced or delayed cooling energy. Zhou and Cao [5] quantified energy flexibility of an integrated thermal/electrical energy system. Based on the proposed energy dispatch strategy, 48.1% of basic electric load can be covered by flexible electricity. Table 2 provides a holistic overview on demand-side flexibility, including Smart HVACs [37][86], appliances in buildings [87][88], integration of electric [36][89] and hydrogen vehicles [90][38], power-to-heat [91][92] and peer-to-peer energy sharing [93][94]. Zhou [95] studied demand-side energy flexibility of an integrated PCM walls, BIPVs, and active air-conditioning system. Results indicate that the flexibility can reduce the annual import cost by 6.1%.

In addition, energy flexibility from power plants has also been studied, as summarized in Table 3. Hou et al. [96] studied probabilistic duck curve for high PV penetration, and concluded that the retrofit on coal-fired units can enhance the power system flexibility. Zhao et al. [97] studied energy flexibility enhancement strategies of coal-fired CHP plants, i.e., power to heat and auxiliary heat source. Results showed that power load factor can be improved, together with the improvement in net annual revenues. Furthermore, energy flexibility enhancement from power plants has also been studied by integrating multi-scale steam turbine energy storages [98], carbon capture and storage [99]. However, economic incentive investments in generation units are required.

Table 2. A holistic overview on demand-side flexibility.

Strategies	Studies	Energy system types	Mechanism	Results
Smart HVACs	Zhou and Zheng [37]	A high-rise office	short-term prediction for real-time control on HVAC systems	Peak value of grid import power can be reduced from 500.3 to 195 kW by 61%.
	Bianchini et al. [86]	Residential apartments	Model predictive control strategy	Optimal control on HVAC systems and storage devices
Smart appliances	Afzalan and Jazizadeh [87]	Residential building	Flexibility provided by demand reduction, in terms of electric vehicle, wet appliances and air conditioning	The case analysis for only 20% participation shows the demand reduction of around 160 MWh for a 2-h event.
	Chen et al. [88]	Residential building	Forced and delayed energy flexibility provided from schedulable and non-schedulable appliances.	Smart appliances can provide potentials for the balance between energy supply and demand.
Electric vehicles	Zhou and Cao [36]	A high-rise office	EV can shift the grid power from off-peak to peak period for demand coverage.	The proposed power dispatch strategy can shift 96.8% of the grid electricity from the off-peak to peak period.
	Salpakari et al. [89]	Residential houses	Self-sufficiency of renewable energy can be improved by transferring into EV charging station	8–33% cost savings can be achieved by the proposed optimal control, whereas the battery degradation needs to be well managed.
Hydrogen vehicles	He et al. [90]	Residential community	A H2-based interactive energy sharing network	the H_2-based energy sharing network is economically competitive, even considering fuel cell degradation cost, when the grid feed-in tariff of renewable energy is reduced by 40%,
	He et al. [38]	Residential community	Microgrid energy sharing, renewable-to-vehicle interaction and heat recovery for efficiency improvement of hydrogen systems.	By adopting the integrated approaches, the maximum mean hourly grid power and the annual energy cost can be reduced by 24.2% to 78.2 kW and by 38.9% to 1228.5 $/household.
Power-to-heat	Salpakari et al. [91]	Residential apartments	Power-to-heat conversion with thermal storage to absorb surplus power	90% of renewable energy can be shared for district heating.
	Kirkerud et al. [92]	District heating system	Power-to-heat solutions to address the large surplus Nordic power in district heating systems	Power-to-heat conversion is a competitive strategy to penetrated intermittent renewable energy.
Peer-to-peer energy sharing	Liu et al. [93]	university campus, commercial office, and high-rise residential buildings	Onsite surplus renewable energy can be shared and traded to the neighborhood following the volume-price theory.	The proposed peer trading strategy can reduce net grid import by 18.54%, carbon emissions by 1594.13 tons and net electricity bill by 8.31%.
	Lüth et al. [94]	Electricity market	Battery for cooperating, trading and balancing supply-demand operations	31% cost savings can be achieved by end-users through peer-to-peer trade and private storage.

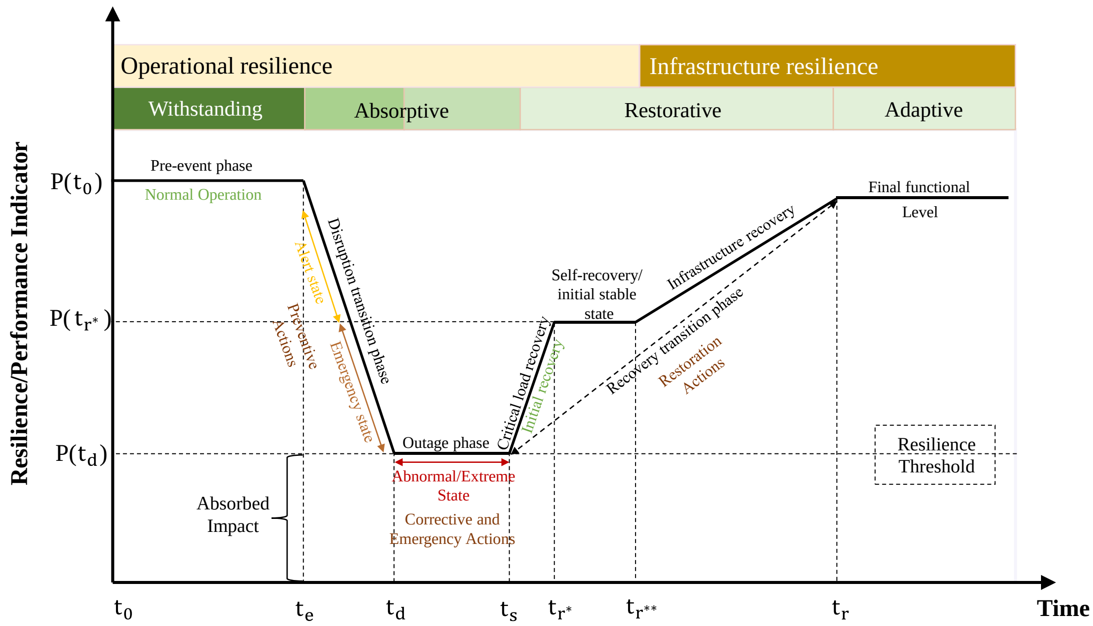
Table 3. A holistic overview on energy flexibility from power plants.

Strategies	Studies	Energy system types	Mechanism	Results
high temperature thermal energy storage	Cao et al. [100]	coal-fired power plant	Thermal energy storage to integrate fluctuated renewable power and improve load flexibility	The net power can be improved up to 6.23% through the integration of thermal storages.
regulation on extraction steam of high-pressure heaters	Zhao et al. [101]	a 660-MW supercritical coal-fired power plant	the increase in the number of throttled valves and/or the degree of feedwater bypass for performance improvement	improvement in power ramp rate in a minute, power capacity, and energy capacity of a coal-fired power plant
steam turbine energy storage	Wang et al. [98]	coal-fired thermal power plant with steam turbine energy storages	feedwater bypass throttling and extraction steam throttling	load flexibility can be effectively improved through the integration of steam turbine energy storages
time varying control	Wang et al. [102]	thermal power plant with heat storage	stepwise regression-based smart charging on boiler heat storage	The coal consumption rate can be decreased by 0.47%.
Stimulus-response control strategy	Zhou et al. [103]	virtual Power Plant	edge computing-based independent decision making for each agent (distributed renewable systems)	dynamic and automatic exploitation on energy flexibility can be achieved with adapting to the change of stimulus signals,
Mixture in power supply	Brouwer et al. [99]	power plants with Carbon Capture and Storage	Stochastic residual load and intermittent renewables will reduce the efficiency of power plants	energy-based market model needs to provide insufficient revenue, so as to incentivise investments in generation capacity

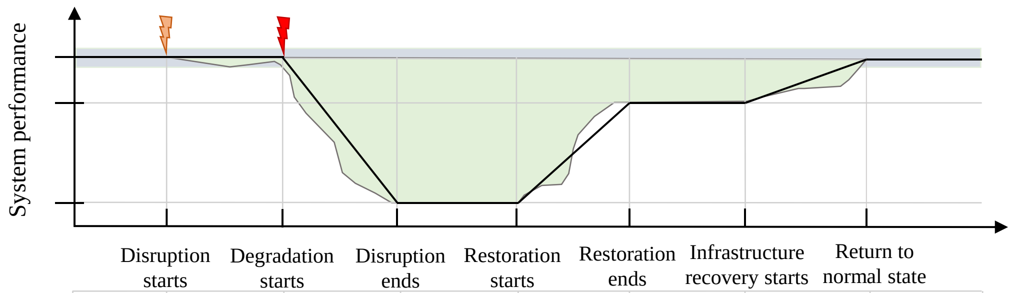
3.2.5. Resilience

Generally, there is no unified concept in energy resilience. Energy resilience mainly refers to the ability to maintain the service level to normal operation [104][105]. Power systems resilience indicators are standardized and categorized throughout all phases [106]. Power system resilience is capability to reduce the likelihood of blackout or wide power outages due to high-impact and low-probability (HILP) events [107]. Perera et al. [108] quantified the effect of climate change on renewable penetration and grid interaction. They concluded that climate change will lead to 34% increase in grid integration level and 16% decrease in power supply.

Fig. 4 demonstrates resilience curves in time during the disruption event, together with performance comparison between resilient and traditional microgrid under stochastic disruptions. As shown in Fig. 4(a), when suffering from extreme events, system energy resilience mainly includes operational and infrastructural resilience. The former refers to withstanding the impact of extreme events with responding, recovering and restoring services. The latter refers to mitigate the impact through restorative and adaptive services. The comparison between traditional and resilient energy system, as shown in Fig. 4(c), shows a higher system function level, and a shorter time-duration for recovering to the targeted level. Table 4 lists energy resilience quantification approaches, in terms of strategies, physical meaning and mathematical equations. Researchers mainly focused on resilience costs, recoverability, adaptability, and stability. Strength without resilience will lead to fragility and severe failures once the threats are outside the designed boundary [111]. Similarly, district energy systems without resilience will be completely destroyed when suffering from disruption. Ahmadi et al. [112] comprehensively reviewed energy system resilience, from perspectives of concept definition, resilience characters and states, modeling features, approach and solutions.



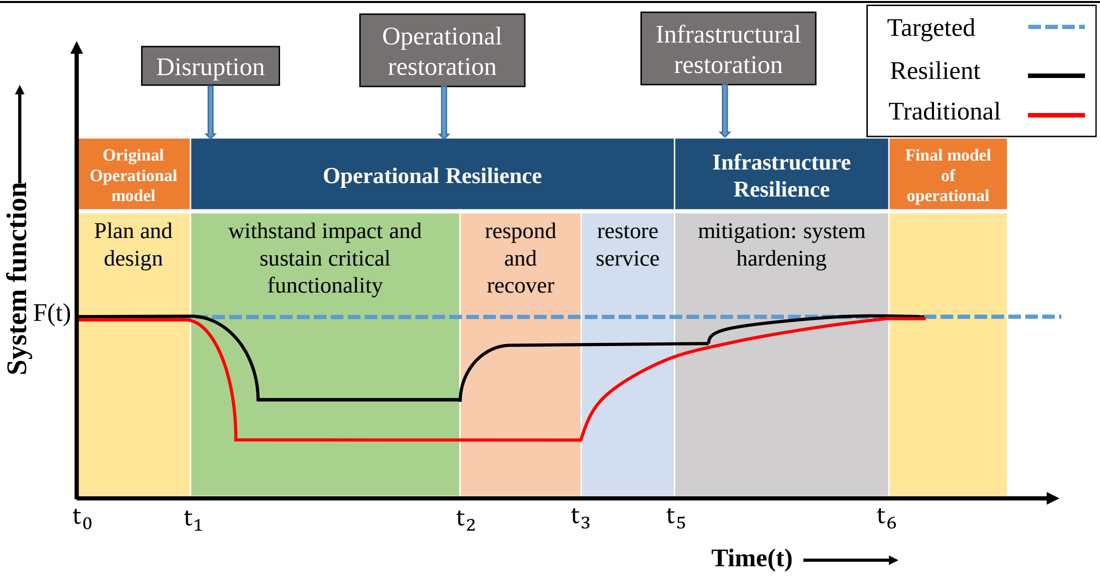
(a)



Phase	0	1	2	3	4	5	6	7
Resilience type	Operational					Infrastructure		
System state	Normal	Disrupted						Normal
Characteristics	Notice Prepare	Avoid Resist	Retreat	Recover			Adapt	
	Reliability	Robustness	Modularity	Recover capacity			Learning capacity	
Actions	Preventative		Emergency			Preventive		

Performance (approximation) Performance (real) Normal operation range Service loss

(b)



(c)

Fig. 4. (a)(b) resilience curves in time during the disruption event [106][109]; (c) performance comparison between resilient and traditional microgrid under stochastic disruptions [110].

Table 4. Summary of energy resilience quantification

Strategies	Studies	Physical meaning	Mathematical equations	Terminology
adaptive capacity, absorptive capacity, and recoverability	Francis and Bekera [113]	absorptive capacity	$R=\frac{F(t)_D}{F(t)_E}\frac{F(t)_R}{F(t)_E}S_P$ $S_P=\frac{t_D-t_E}{t_R-t_E}$	$F(t)_D$: the performance level of the system at the post-disruption time; F(t)R- initial post-disruption equilibrium state; $F(t)_E$: the performance of the original stable system; t_E: time at the event start; t_R: at the completed restoration; t_D: in the worst damaged condition
resilience costs for decreased system productivity and recovery activities	Hines et al. [114]	resilience costs	$RC=\frac{SIC+MREC+TREC}{TMV}$	SIC: systemic impact cost; MREC: market recovery effort cost; TREC: transportation recovery effort cost; TMV: target market value of production
resilience cost for actions and cost loss from inability	Henry et al. [115]	Sum of cost for resilience action and cost loss due to the inability	$R=\frac{recovery_{(t)}}{loss_{(t)}}=\frac{F(t)-F(t)_D}{F(t)_E-F(t)_D}$ $C=Cost_{resilience\ action}+L_{system\ disruption}$	$Cost_{resilience\ action}$: a function of the cost incurred in implementing the resilience action; $L_{system\ disruption}$: the cost loss incurred due to the inability of the system to perform at a normal level due to system disruption
recoverability	Ouyang and Dueñas-Osorio [116]	Ratio of performance change after restoration efforts under disruption to the target performance	$R(t)=\frac{\int_0^T F(t)dt}{\int_0^T F(t)_E dt}$	F(t): performance change after restoration efforts under disruption; $F(t)_E$: the performance of the original stable system
adaptability	Jufri et al. [117]	the ratio of the system parameters at restoration time to the system parameters prior to the disruptive event	$Adaptability=\frac{\Phi_{enhanced}}{\Phi_{pre\text{-}event}}$	$\Phi_{enhanced}$: system parameters at restoration time; $\Phi_{pre\text{-}event}$: system parameters prior to the disruptive event
performance difference under normal and disruption conditions	Bruneau et al. [118]	accumulated performance difference between normal and disruption conditions	$R=\int_0^{T_D}(F(t)_E-F(t))dt$	—

Sum of dependent variables with weighting factors	Martišauskas et al. [119]	Weighted sum of unserved energy (energy demand that exceeds the energy supply) and energy cost increase (increased cost due to a specific disruption)	$ESC=\exp(-\alpha_1 \cdot UE \cdot \exp(Y_s) - \alpha_2 \cdot ECI \cdot \exp(Y_s))$ $ECI=\frac{FC-BC}{BC}$ $UE=1-\frac{P}{D}$	UE: unserved energy; ECI: energy cost increase; P: energy production; D: energy demand; α_1 and α_2 are weighting coefficients
Stability index	Molyneaux et al. [120]	stability when redundancy and diversity of energy systems go into/out from the system boundary	$S=\rho_i \log\rho_i$	ρ_i: probability that energy will pass to any predator
Resilience index	Moslehi and Reddy [121]	Relative percentage between maximum possible imposed costs and imposed costs in the failure mode	$R=\frac{IC^{max}-IC}{IC^{max}}$ $IC=OC+\sum_k FL_k \times PC_k$	IC: cost in the failure mode; PC: penalty cost
Remaining network utilization	Lai and Illindala [122]	the average ratio of the remaining capacity after satisfying the current load demand to the total network capacity at each time	$aru=\frac{\sum_{t=1}^{T} ru_t}{T}$	aru-average remaining network utilization index

3.3. Roles and relationships among reliability, robustness, resilience and flexibility

Differences between reliability and resilience mainly exist in time dependence, severity, frequency, and magnitude of threats [123][124][125][126][127]. Researchers defined reliability as system operation under threats within threshold in high probability, while the resilience is out of threshold in low probability [124][125][126][127]. Robustness of energy systems refers to the system operational function under cascading failures from random attacks or parameter uncertainties [128]. Energy flexibility refers to demand response to avoid excessive production and to stabilize energy networks [5].

Uncertainty-based robustness optimization has been applied to enable the system function properly even when the structure is broken or damaged. Generally, uncertainty-based robustness optimization includes uncertainty quantification, model development, optimization function and constraints, optimization engine and robust analysis [129][130]. Wang et al. [131] conducted multi-objective optimization with Monte Carlo simulation to evaluate the robustness of integrated energy systems. The Shannon-entropy-based final optimum solution shows more superior performances over other solutions, in terms of total cost, carbon emission and probability of failure. Majewski et al. [132] proposed a two-stage robustness trade-off approach to ensure security of energy supply with low additional costs. Kotireddy et al. [133] developed a non-probabilistic robustness assessment methodology for robust energy system planning, so as to avoid significant change in energy use, cost and comfort as designed, due to uncertainties of external factors. The proposed approach can be adopted by designers and consultants for robust design.

Fig. 5 demonstrates relationship among reliability, robustness, resilience and flexibility in multi-energy systems. Comprehensive consideration on multiple indicators can ensure energy supply reliability and grid stability in decarbonization pathways. Abedi et al. [134] provide a systematic approach to identify the vulnerability of power systems and enhance robustness and resilience. Shandiz et al. [135] proposed a resilience framework to survive the energy community under chronic stresses and extreme events. Nik and Moazami [136] applied collective intelligence with automatic shock absorption to enhance demand flexibility and climate resilience. Results indicate that, during extreme climate events, Collective intelligence with 60 min and 15 min can decrease annual heating demand by 38% and 44%, respectively. Gracceva and Zeniewski [137] proposed a systematic approach on energy security of a district community, from perspectives of stability, flexibility, adequacy, resilience and robustness. The method can promote system decarbonization with energy supply security under climate change.

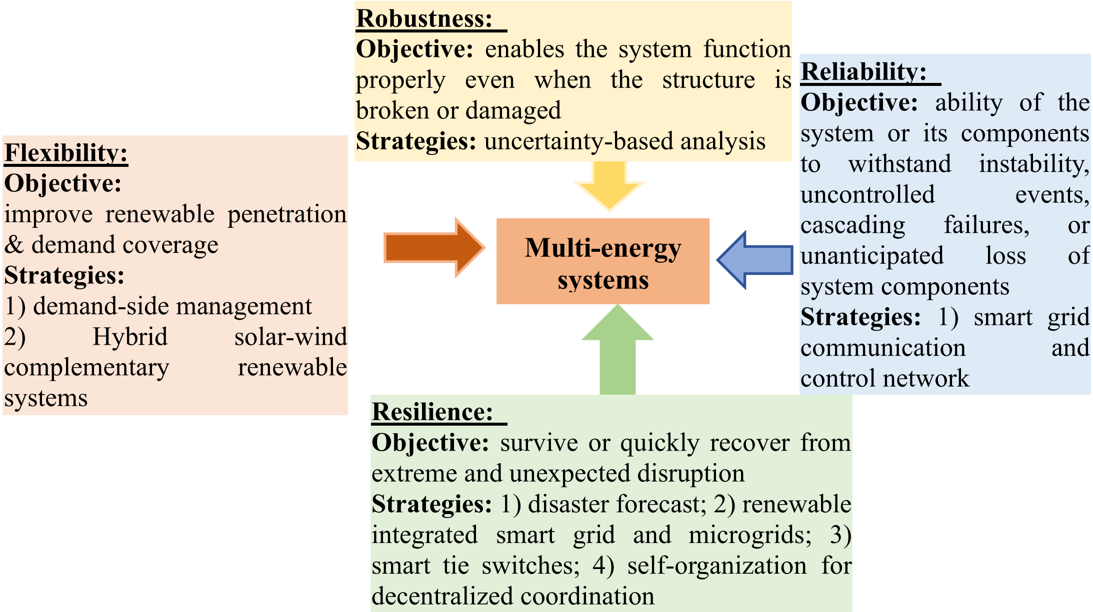


Fig. 5. Relationship among reliability, robustness, resilience and flexibility in multi-energy systems.

4. Approaches for energy resilience enhancement in district energy systems

4.1. Types of threat sources

Fig. 6 demonstrates threat sources, district power systems, and security challenges. Generally, security in district energy systems can be classified into infrastructural security, operational security, data management security, regulation, and policy [138]. Sharifi and Yamagata [139] indicated that threat sources mainly included cyber-attacks, terrorism, technical deficiencies, and market volatility. Physical attacks, cyber-attacks, natural disasters, and random failures are major threats to energy security, and security challenges [140]. The climate change and climate-induced uncertainty will lead to an increase in average frequency of nuclear power outrage [141]. Yalew et al. [142] analysed the impact of climate change on energy consumptions, and provided a multi-model framework for cross-scale energy planning. The severe drought in Finland will lead to power inadequacy due to the high reliance of national energy on hydropower [143]. In terms of cyber threats, cyber-physical security can be improved through a holistic resilience cycle (HRC) [144].

Generally, energy security is involved with the chain of power generation, transmission, storage and distribution, as summarized in Table 5. The transition from centralized power plants towards distributed energy generation unit can improve energy efficiency and reliability [145]. Sun et al. [146] developed a fuzzy inference to predict security weaknesses in transmission networks. By calculating probabilistic fuzzy risks and reducing uncertainties in predicting when and where extreme events occur, energy flexibility and robustness can be improved. In respect to energy storages, hydrogen storage in H_2 tank shows high pressure, e.g., 700 bar in “Toyota FCHV-adv” [147], leading to security anxiety for users. Re-use of EV battery and smart charging/discharging can improve the power supply reliability. From the end-users’ side, onsite renewable power supply in buildings can enhance the self-consumption and energy independence level, whereas the intermittence, variability and fluctuation of renewable energy will provide challenges for energy supply reliability [148].

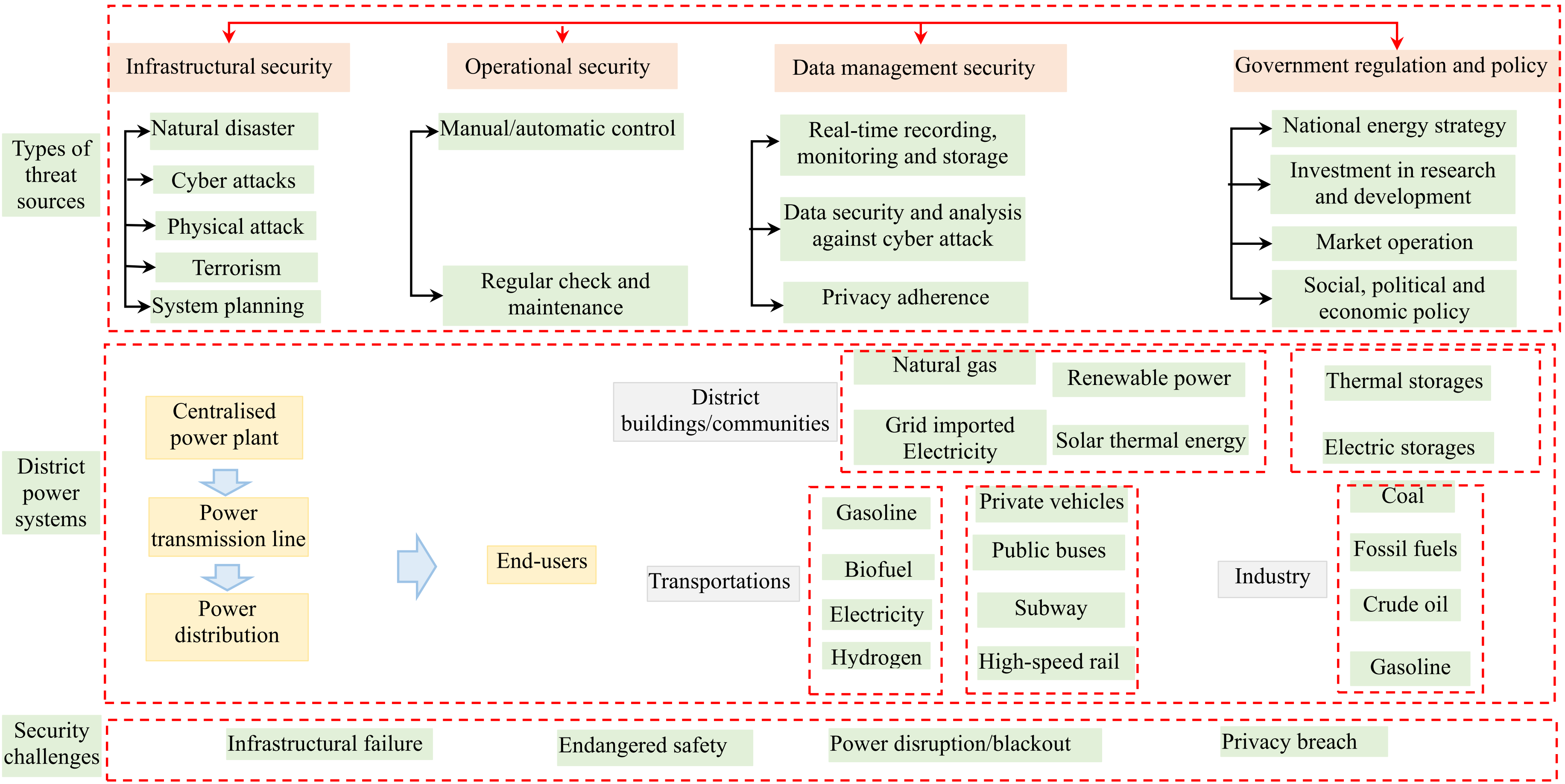


Fig. 6. Overall framework on threat sources, district power systems and security challenges.

Table 5. Energy resilience throughout the energy supply-demand chain.

Energy supply-demand chain		Studies	Key security aspects	Methodology	Results
Power generation		Johansson [148]	variability and intermittence of renewable electricity; energy carrier, effective policy and regulations	1) keep biodiversity and sustainable productivity; 2) diversity of renewable energy types; 3) dependence on diverse energy sources	A framework/typology for energy security with supply and demand
		Sapkota et al. [149]	climate change	Integration of micro-hydro and solar power systems	CO_2 emission can be significantly reduced by the integrated solutions
		Mutani et al. [150]	energy supply blackout	reduce energy consumption, increase energy production, and an optimal energy supply and demand.	Actions to reduce risk of energy supply blackout are consistent with Integrated National Plan for Energy and Climate
Power transmission		Clegg and Mancarella [151]	electrical and gas network flow for heating	an electricity-heat-gas transmission network model for cost optimization considering nodal gas price	The proposed hybrid strategy can lead to 75% reduction in carbon emission and 24% decrease in conventional generation peaks.
Energy storage	Hydrogen storage	Wijayanta et al. [152]	energy consumption and H_2 loss in the storage process	Comparative analysis	NH_3 shows the highest total efficiency.
		Zhang et al. [153]	burst pressure, fiber damage state and fatigue lifetime	finite element models for failure prediction	factors controlling and monitoring are critical for structural strength
	Electrochemical battery	Moore et al. [154]	back-up power to critical infrastructure	Re-use of EV battery	community resilience can be ensured during disaster with circular economy
		Galvan et al. [155]	Power supply reliability under moderate and heavy damage conditions	networked microgrid, roof-top solar photovoltaic and battery	Anti-power outrage solution through smart charging/discharging on battery and resilience improvement of the distribution grid to natural disasters
Power distribution		Hussain et al. [42]	extreme weather condition for power outage	Reducing the impact of major disruption through proactive scheduling, outage management, feasible islanding, and advanced operation strategies	resilience-oriented operation through microgrid operation

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4.2. Mechanism on system recovery through energy resilience

In order to recover quickly and efficiently after suffering from threat, mechanism on system recovery was explored in this subsection. Generally, system recovery through energy resilience can be from following aspects:

1) natural disaster forecast on power system disturbances [156];

2 smart grid and microgrids with distributed renewable systems;

3) additional tie switches;

4) self-organization [157] for physical grid topology change into energy groups: autonomous agents based decentralized coordination.

In order to prevent and mitigate the hazard impacts, Koraz and Gabbar [158] proposed a risk analysis and self-healing approach through a resilient micro energy grid (MEG) configuration mode. The simulation testing results indicate that the MEG shows high self-healing capability for various hazardous scenarios, together with improvement in energy efficiency and decrease in gas emission. By changing the urban integrated energy system into various “islands” after the extreme event, Li et al. [159] proposed a coordinated multi-energy system with energy complementarity to improve system resilience. By applying physical and Information & Communication Technology (ICT) to automatically form local energy groups, energy demand can be well covered during power outage period [160].

4.3. Defense measures for energy resilience

Resilience of energy systems is case-dependent, and objectives of resilience research should be clarified. Resilience of power systems includes resistance and restabilization capacity for disruptions, and effective recovery strategies are necessary with respect to reliability, vulnerability or robustness [161]. Compared to reliable infrastructure and services in urban areas, the resilience of power systems in emerging developing rural areas is relatively lower. Mazur et al. [162] proposed a resilient rural power system framework, from technological, social, and economic perspectives. Sharifi and Yamagata [139] considered planning and design criteria to assess urban energy resilience, with respect to ‘availability’, ‘accessibility’, ‘affordability’, and ‘acceptability’. Controlled objectives include infrastructure, resources, land use, urban geometry and morphology, governance, socio-demographic aspects and human behavior. Generally, three categories for power system resilience management include ‘resilience-based planning’, ‘resilience-based response’, and ‘resilience-based restoration’ [107]. Molyneaux et al. [163] called for multi-disciplinary efforts to enhance the system adaptive capacity for ecological resilience, psychological resilience, risk management and energy security. They summarized that general ways included diversity in fuel types, spare capacity in energy production and efficiency in power supply. Fig. 7 classifies effective measures to improve energy resilience, in respect to prevention, correction and restoration during both planning and operation stages. As shown in Fig. 7, there are totally seven types of counteractive measures to improve energy resilience.

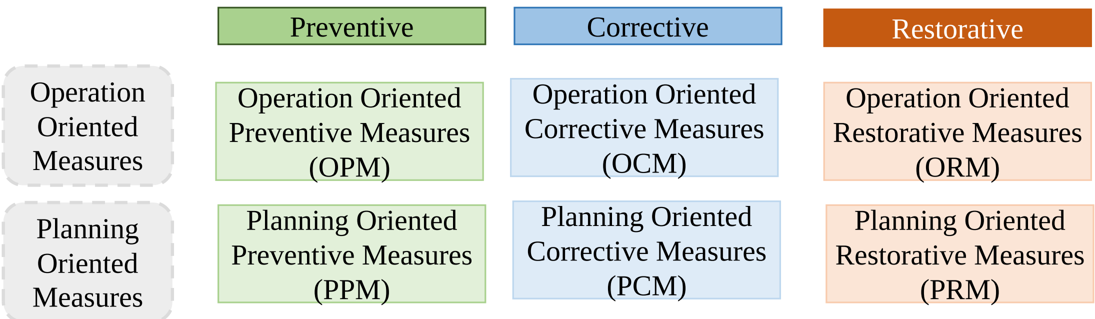

Fig. 7. Classification on effective measures for resilience improvement [123].

In respect to resilience-based planning approaches, Younesi et al. [164] reviewed microgrid potentials for resilience enhancement of power systems, and concluded that the transmission line is the most vulnerable section when suffering from natural disasters. Fig. 8 demonstrates energy planning for resilience enhancement. By incorporating feedbacks from performance assessment in energy planning models, dynamic iteration through the closed-loop cycle can achieve the optimal energy planning solution. The planning of renewable energy is one of effective ways for national energy security, when suffering from stochastic threats and disruptions [165]. Mishra et al. [166] designed a microgrid as a back-up source to improve grid resilience under physical and cyber threats. Resilience measures mainly include potential threats, identification of vulnerabilities, and design of mitigation strategies. Cáceres et al. [167] studied the synergistic operation on hydropower and solar power for capacity loss compensation and mitigate the climate change impact on energy systems.

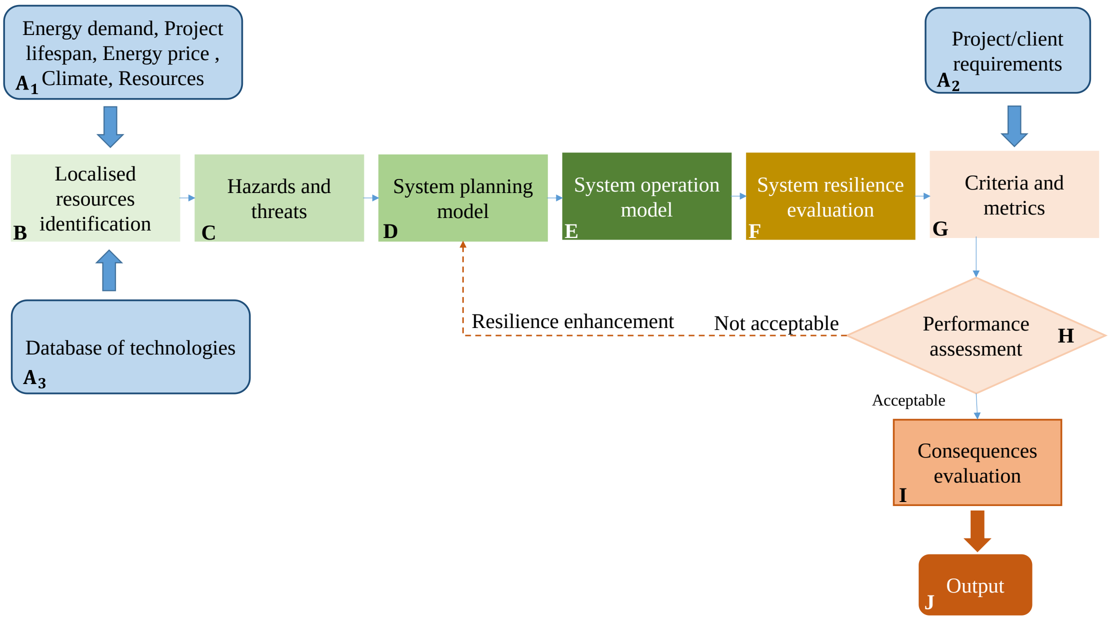

Fig. 8. Resilience planning process--steps are labelled from A to J [29].

In respect to resilience-based response, Diahovchenko et al. [168] investigated two effective strategies for grid resilience, i.e., microgrids with distributed renewable systems and additional tie switches. The former can avoid the power blackout with cleaner power supply, and the latter can flexibly isolate the faulted section of distribution system, so as to decrease energy losses and provide service restoration. In terms of energy supply, Kosai and Unesaki [169] explored diverse fuel types for local energy security, as demonstrated in Fig. 9, including coal, nuclear, hydro, oil and etc. As shown in Fig. 9, local energy security can be ensured from perspectives of multiple energy supply sources and energy storages. They found that the vulnerability of battery and solar is dependent on the time span. In respect to diverse energy sources, energy mix proportion was optimized to maximize the energy security [170]. Results showed that, in the case study, the optimal energy mix consists of 30% nuclear, 50% renewable energy and 20% gas. With respect to renewable integrated energy systems, Rosales-Asensio et al. [171] investigated the outage survivability of a PV-battery system as an alternative to the diesel-based emergency system. Results showed that $ 112,410 can be saved over the 20-year life cycle operation. Lagrange et al. [172] optimized economic profitability and resilience capacity for an integrated system with solar PV, battery and diesel generator. Results showed that the system can increase the minimum service time resilience for more than 34 h. From perspectives of power grid, operational mode isolation towards microgrids can enhance resilience, in respect to different forms, like networked microgrids, dynamic microgrids and multi-energy networks [42]. By forming microgrids in districts, innovative strategies for disruption minimization include proactive scheduling, outage management, feasible islanding, and advanced operation strategies. Furthermore, synergies can be activated to respond to the disruption. In addition, advances in artificial intelligence have been applied to enhance resilience-based response. Considering uncertainty and high dimensionality in power distribution systems, Hosseini and Parvania [173] applied artificial intelligence for fault diagnosis and detection, security enhancement and uncertainty-based decision making (as shown in Fig. 10), to enhance the resilience of power distribution systems. The proposed approach mainly includes algorithm searching and decision evaluation.

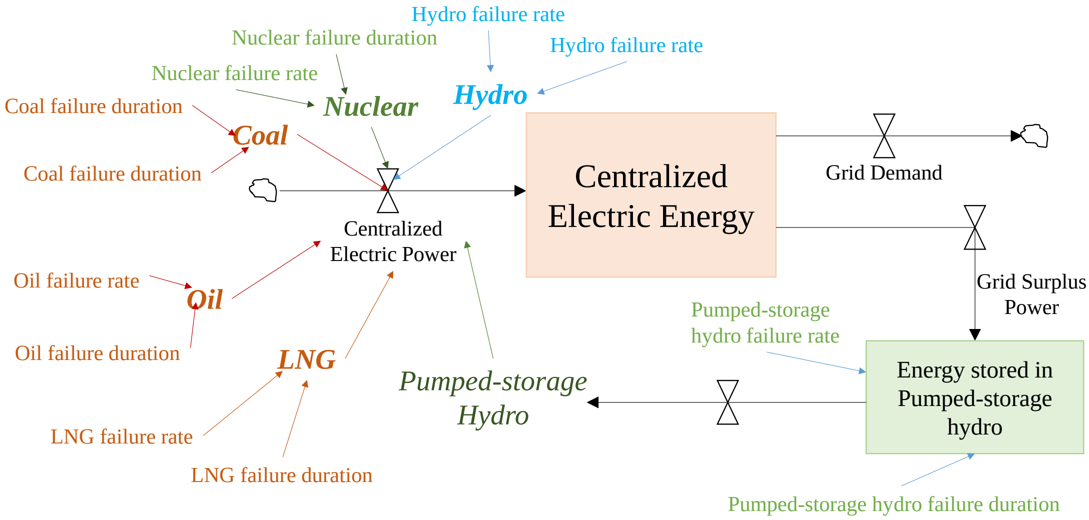

Fig. 9. Diverse fuel types for grid power supply [169].

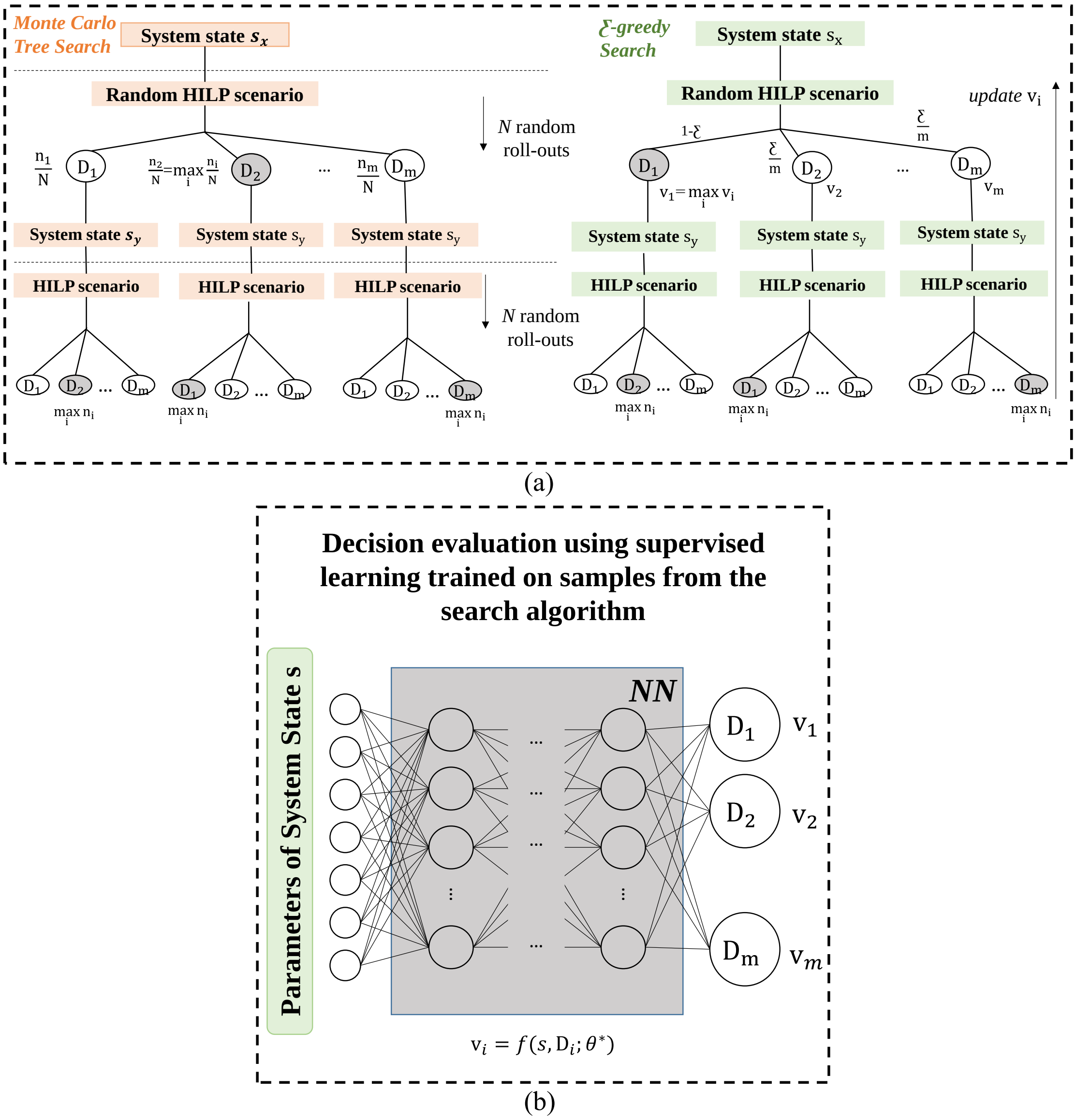

Fig. 10. (a) searching algorithms to find decisions; (b) decision evaluation used for unsupervised learning in stochastic operational decision-making [173].

In terms of resilience-based restoration, Salman et al. [174] developed targeted hardening strategies to strengthen the power distribution and improve the system reliability under hurricane hazard conditions, considering failure of poles and decay of distribution poles in power delivery processes. Results indicated that, targeted hardening was more cost-effective than hardening the entire system, without sacrificing system reliability. Fig. 11 demonstrates a resilience-based restoration procedure to normal operation state during extreme weather conditions [175], including weather forecasting, data gathering, coordination between operators and repair crews, restoration, and corrective actions. Measures to improve energy resilience for climate mitigation mainly include city energy shed (network of power plants and power flow) [176], inter-city energy migration framework [6], grid architecture redesign, fuel mix and grid hardening measures [177]. Furthermore, from the perspective of a regional district energy community, a spatiotemporal energy sharing network through daily transportation in two geographical locations [3] can achieve regional energy balance, enhance renewable penetration, cruise anxiety mitigation and so on.

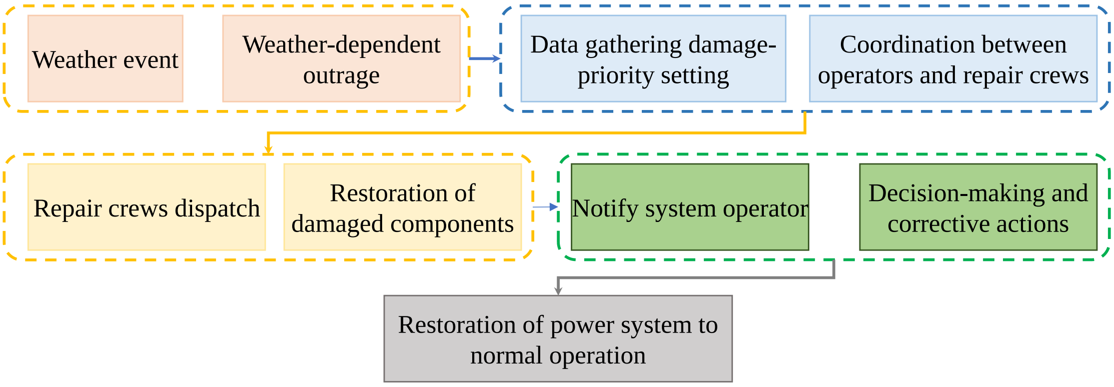

Fig. 11. Resilience-based restoration during extreme weather conditions [175].

Transition from centralized to distributed energy prosumers can also improve the resilience-based restoration capability when suffering from sudden attack or extreme climate. As demonstrated in Fig. 12, the transition from centralized power plants to prosumer-islanded microgrids can reduce energy service domain and enhance the survival probability when suffering from centralized power attacks. However, the failure of each centralized power supply station will lead to the power outage for associated end-users. The transition towards prosumer-to-interconnected microgrids with extension on power transmission lines, as shown in Fig. 12(c), can enhance the power supply reliability, even when several centralized power supply stations can't operate properly. Furthermore, the transition towards distributed energy prosumers, forming an energy sharing and trading network, as shown in Fig. 12(d), can maximise the energy resilience and reliability, as each agent can become power supply agent.

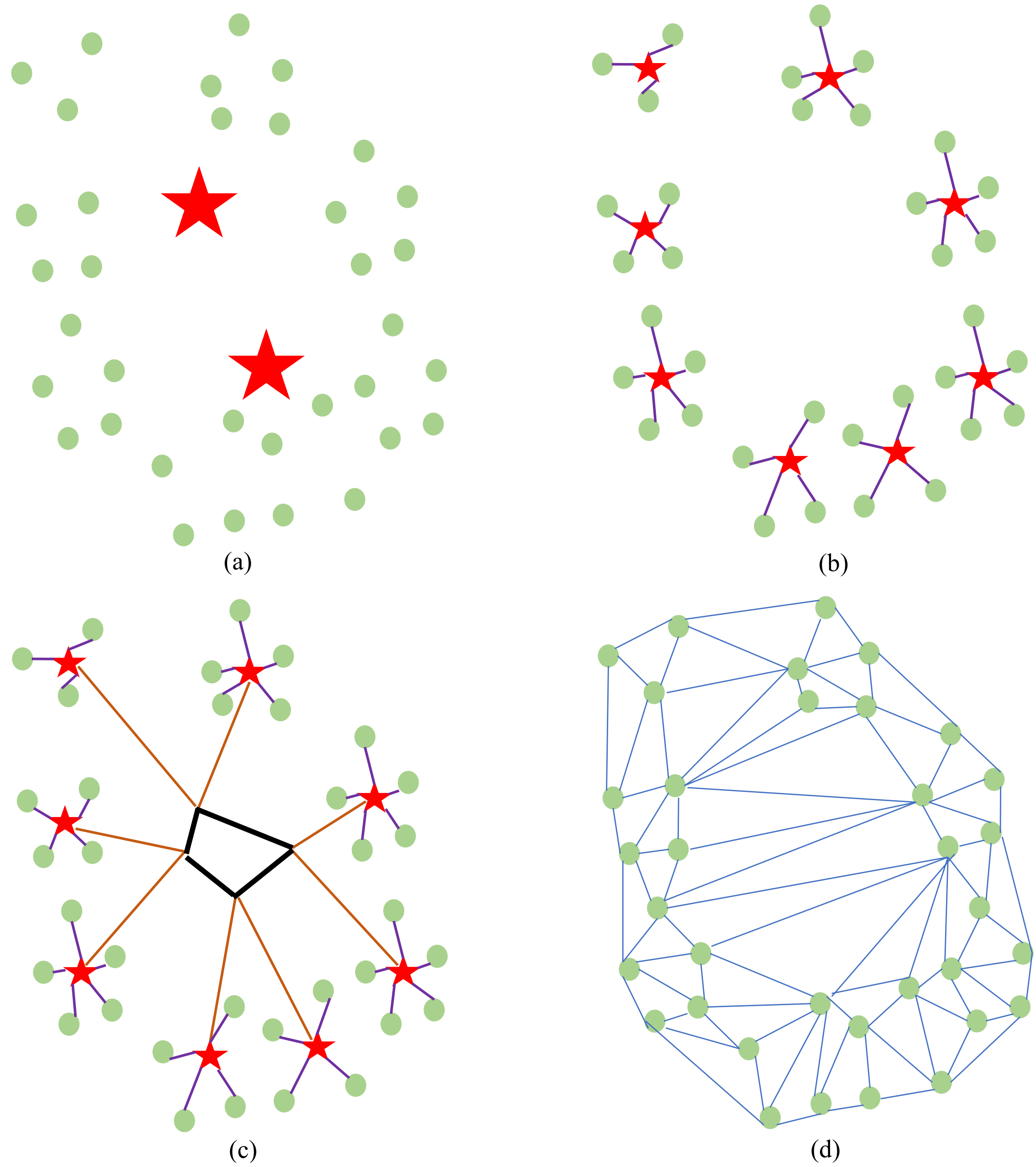

Fig. 12. Typology of centralized energy consumer to distributed energy prosumer: (a) centralized power plant; (b) prosumer-to-islanded microgrids; (c) prosumer-to-interconnected microgrids; (d) distributed energy prosumer.

In order to achieve the energy resilience, cross-border trading through spatiotemporal energy complementation has been studied to improve regional energy security [178]. Furthermore, in the Guangdong-Hong Kong-Macao Greater Bay Area, Zhou [6] proposed a novel spatiotemporal energy network, together with advanced energy pricing incentives to promote participations from different stakeholders (like building and vehicle owners), as demonstrated in Fig. 13. The formulated energy sharing network can improve the renewable energy penetration and decarbonization level during normal periods, and enhance power supply reliability during extreme weather or war periods. Furthermore, with the rapid development in digitalization and decentralization technologies, new chances are provided for energy resilience enhancement [179] with decarbonization potentials. In order to incentivise multi-stakeholders' proactivity, Zhou [180] explored flexible power sharing strategy and advanced energy pricing policy. Results can promote the transition of building and vehicle owners from economic payer to income earner.

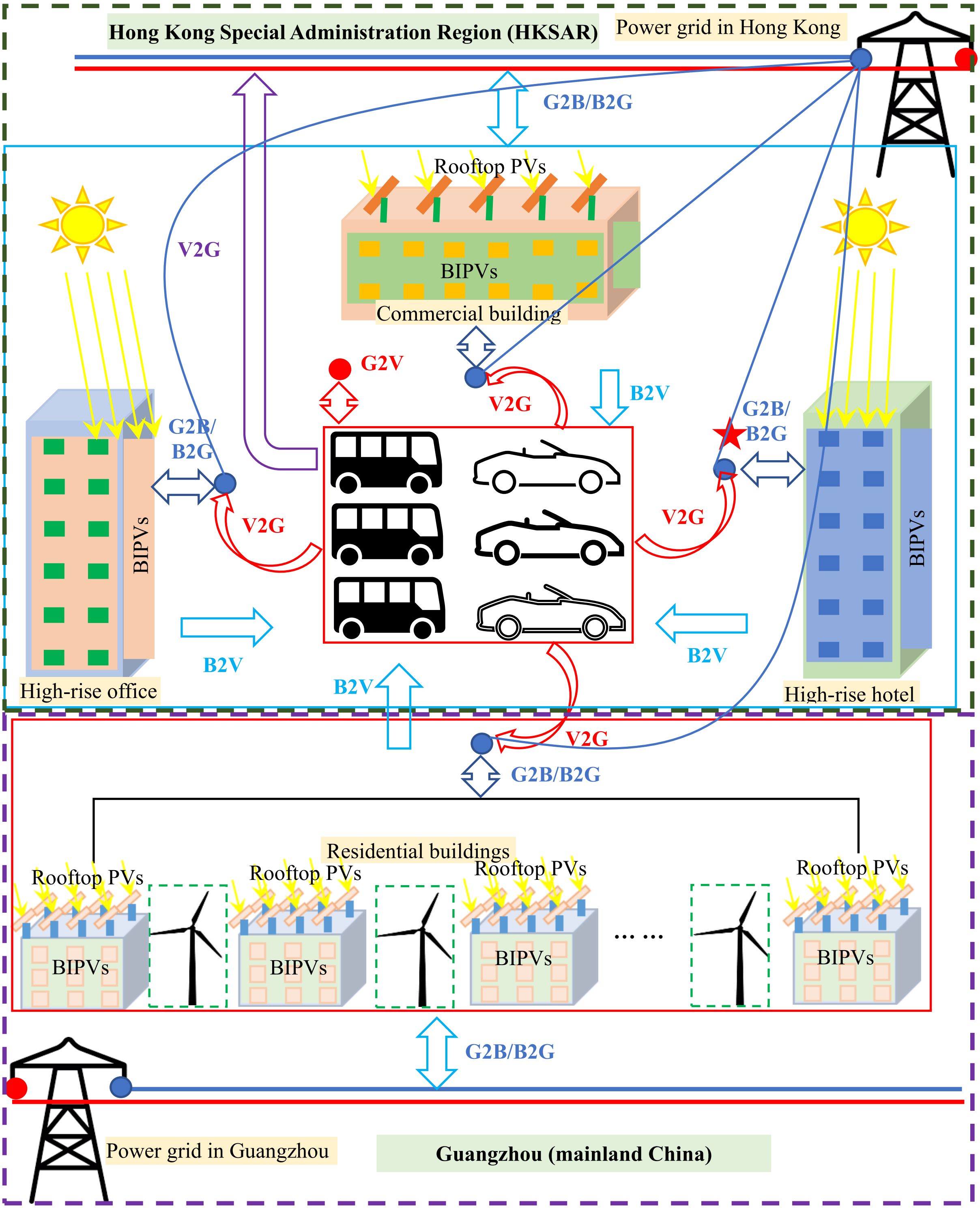

Fig. 13. An inter-city energy migration network for urban decarbonization and energy resilience with mobile vehicles integrated energy systems [6].

5. Applications of energy resilience in district energy community

5.1. Building energy and urban morphology

Due to the considerable proportion of energy consumptions in building sectors (around 40%), energy resilience in urban energy systems has recently attracted researchers' interests. Due to the climate change, Attia et al. [181] studied resilient cooling to survive against heat waves and power outages, including vulnerability, resistance, robustness, recovery processes. As demonstrated in Fig. 14, the energy resilience can help the system recover to the normal state, while the traditional system will be out of services when suffering from unforeseeable disruptions. Furthermore, compared to foreseeable disruption, the unforeseeable disruption requires longer time-duration with deeper performance degradation. The robustness of the system can help survive under extreme weather, followed by the recovery to normal performance. Ascione et al. [182] conducted multi-objective optimization on building energy retrofitting considering global warming. In addition, electric vehicle based energy sharing and demand response can help improve building resilience against power outage, in respect to critical load restoration and energy loss. Results indicated that, energy cost can be reduced by around 25% and supply load can be maintained for 7-h during power outage period [183].

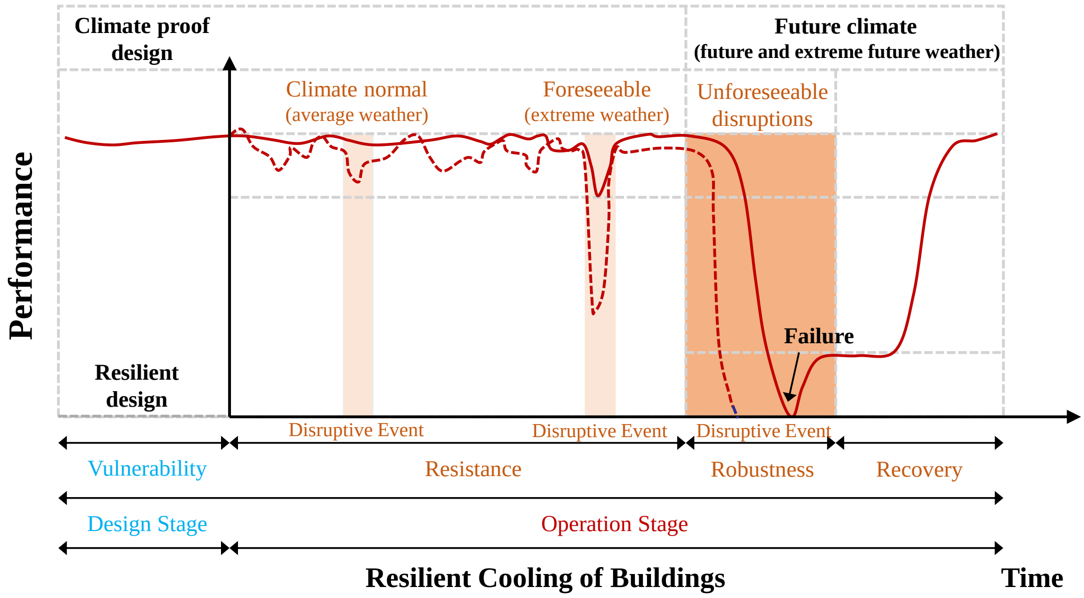

Fig. 14. Resilient cooling [181].

From the perspective of large-scale urban energy systems, Perera et al. [184] conducted co-optimization of an urban energy system under extreme warm and cold weather datasets. Results showed that, energy demand will be increased by 10% and 27% under current building form and urban density, and 20% in energy demand due to extreme weather condition. In respect to an office building with critical loads (like data servers and data processing centers), Rosales-Asensio et al. [185] studied energy resilience of a PV-battery system during the power outrage period. An extension for 4 h on survival time can be achieved in the power cut scenario. Moazami et al. [186] synthesized weather data following dynamical downscaling for robust design under extreme weather conditions, as shown in Fig. 15. By generating datasets under typical weather and extreme weather conditions, reliable energy systems can be designed to survive under extreme weather conditions.

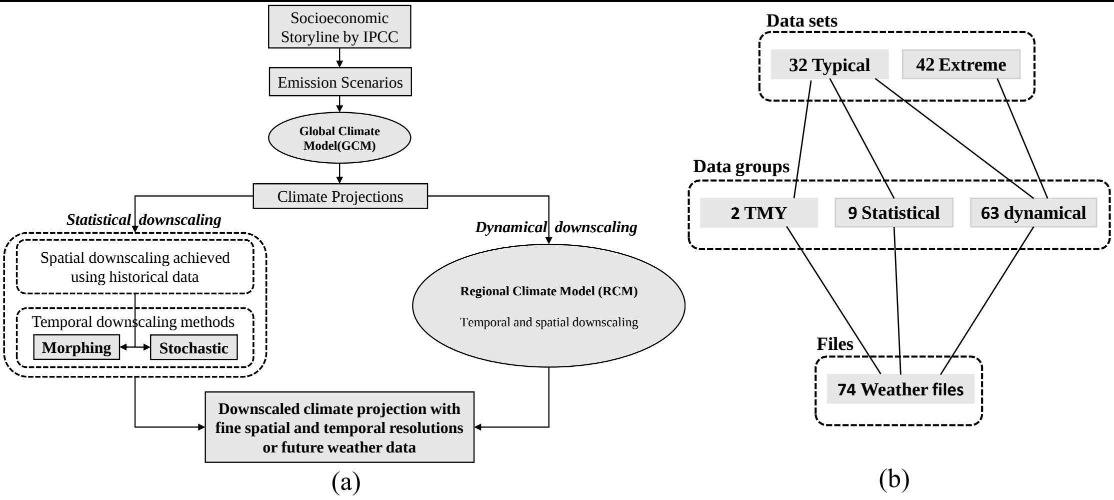

Fig. 15. (a) climate data with spatial and temporal resolution; (b) typical weather and extreme weather data sets [186].

Furthermore, in respect to simulation platforms on urban energy systems, Katal et al. [30] developed an integrated CityFFD and CityBEM platform to investigate the vulnerability and survivability of an urban energy system with over 1000 buildings. Nik et al. [187] comprehensively reviewed climate-resilient urban energy systems, with climate change and input parameter uncertainty. The review can provide frontier guidelines for pathway transition towards a climate resilient energy system. Abbasabadi and Ashayeri [188] comprehensively reviewed urban energy use modeling techniques, with respect to physical model and data-driven models. However, the simplification on urban context, urban microclimate, inter-building effects and human-related factors leads to the prediction inaccuracy.

5.2. Electrification and hydrogenation in mobility-based interactive energy sharing systems

Fig. 16 demonstrates the Vehicle-to-Home interaction for energy resilience, reducing loss of power supply and stabilising grid voltage. Mehrjerdi [189] studied energy resilience provided by vehicle-to-home operation consecutive events. Results indicate that, battery cost can be reduced by about 8%, together with the enhancement in energy resilience via emergency battery swapping. Mehrjerdi and Hemmati [190] studied resilience and self-healing function of vehicle-to-home energy systems. In terms of qualitative analysis on energy resilience of buildings against natural disasters, Tian and Talebizadehsardari [183] explored critical load restoration and quantified minimum energy loss of an integrated EV-building energy system. Smart EVs charging/discharging can decrease energy cost by around 25% and reliably cover demand under 7-h power outage. Roche et al. [191] smartly controlled loads and appliances in vehicle-to-home interactions to improve home energy resilience during power outrage period. Guo et al. [192] studied the impact of vehicle-to-home and renewable resources on energy resiliency and self-scheduling. Results indicate that, the resilience mode can reduce the operation cost by 13%. Zhou et al. [193] comprehensively reviewed multi-directional energy interactions in various types of vehicles for energy efficiency improvement, renewable penetration, demand coverage and system sustainability. Spatial power interaction can address the temporal energy mismatch and improve energy utilization efficiency.

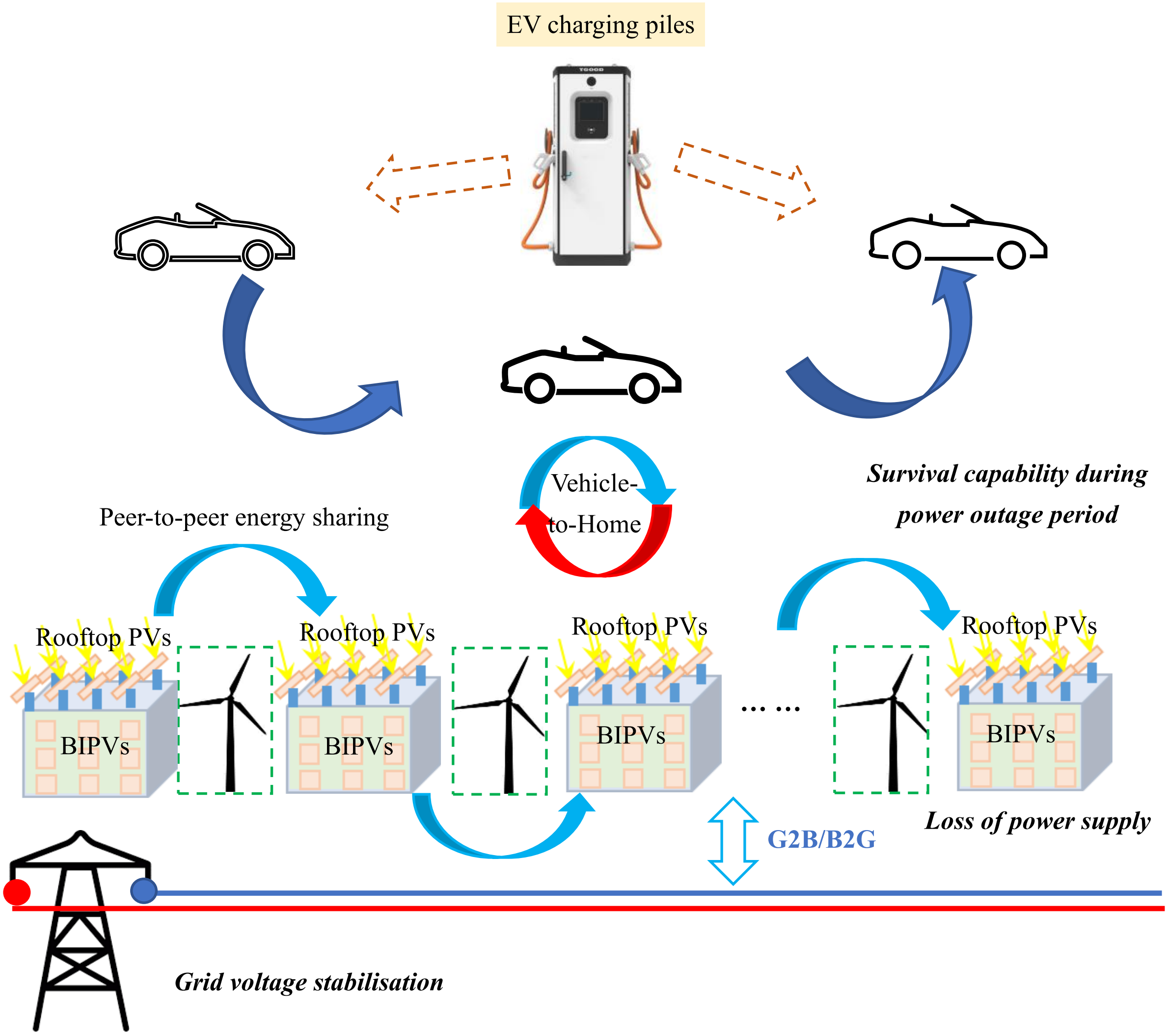

Fig. 16. Diagram on Vehicle-to-Home for energy resilience.

5.3. Microgrids

Considering the vulnerability of power systems to climate change, investment in electricity infrastructure with consideration on energy system resilience is necessary to stabilize the local electricity price [194]. Renewable energy sources, distributed storage for intermittent controllability and less connections in power grid with selective removal of transmission lines instead of random removal, are effective measures to ensure the security on local power energy systems [195]. Mutani et al. [196] studied the planning on energy community with high resilience. The approach can survive the system when suffering from risk of energy supply blackouts, and improve economic-environmental performances. Vehicle-to-grid interaction can exploit EVs to decarbonize district heating systems and increase the power grid stability [197]. Microgrid, a flexible combination via interconnection with power supply units and end-users, can enhance energy resilience during power outage periods, through proactive scheduling, outage management, feasible islanding [42]. In addition to traditional diesel-based emergency supply systems, Rosales-Asensio et al. [171] designed a solar PV and electrochemical battery to improve the outage survivability of microgrids. Results showed that the system can survive for over 4 h when suffering from power outrage events.

Fig. 17 shows energy resilience enhancement strategies during pre-event, on-event and post-event phases, mainly including disaster modeling, forecast and estimation, resilience analysis and resilience enhancement. By receiving feedbacks from post-event phase and incorporating it in pre-event phase and on-event phase, disaster forecast and estimation can help harden the resilience and improve the survivability.

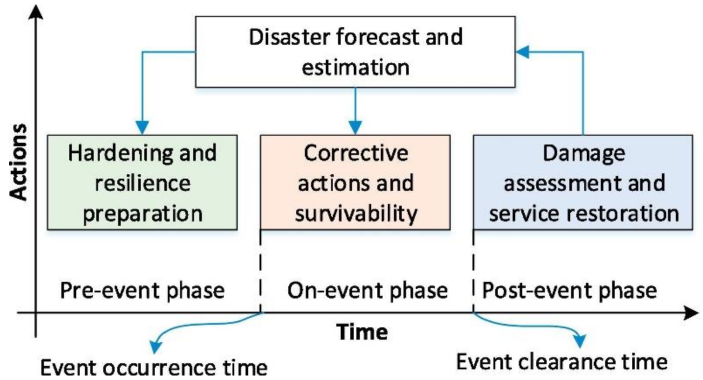

Fig. 17. Strategies for energy resilience enhancement [198].

6. Outlook and recommendations

This state-of-the-art review comprehensively provides energy resilience in smart district energy systems, in terms of diversity and inconsistency of concept definition and quantification approaches, approaches for energy resilience enhancement, correlation with reliability, robustness and flexibility, and practical applications. A clear roadmap was provided to address system complexity and uncertainty, and to enhance survival probability under climate change, extreme weather conditions, and future threats. However, there is no universally acknowledged method on energy resilience quantification. Furthermore, defense measures for energy resilience enhancement are limited within small scales (like single buildings and microgrids), without considering large-scale energy districts. Current situation and future potentials on cross-border energy sharing have not been well evaluated and quantified, with respect to infrastructure construction, dialectical analysis on techno-economic-environmental performance, energy resilience enhancement, and participation willingness from different stakeholders. Future studies can focus on:

1) a universally acknowledged energy resilience quantification approach, comprehensively considering diversity and underlying mechanism for each indicator and pre-event/on-event/post-event phases. Some energy security objectives complement each other whereas others counteract each other [199]. Dimension prioritization and weighting factors for each indicator might be one of effective strategies to address the difference in impact factors.
2) trade-off strategies between enhancement in energy resilience and decrease in energy efficiency [200]. Future district energy systems require comprehensive considerations on both energy efficiency and energy flexibility during normal operation period, power reliability, robustness and resilience during extreme power outage period.
3) expansion from small-scale energy systems to large-scale cross-border energy districts. The transition from centralized power plants to distributed energy prosumers with mobility energy sharing can enhance the regional energy resilience.
4) advanced energy price policies to encourage stakeholders' participation willingness, and overcome contradictions between economic losses (like depreciation costs from V2X interactions) and associated cost savings (like operating cost saving).

In order to address system complexity, roadmaps are identified as follows:

1) development of transient system simulation platform with user-friendly interface for subcomponent integration, energy analytics and optimization;
2) dynamic state and annual energy balance check for every component, subsystem and entire integrated multi-energy systems;

3) interconnection between various energy systems through energy conversion, management, storage and synergistic operation;
4) model transferability, interpretability and applicability for flexible energy systems;
5) correlation among energy resilience, reliability, robustness and flexibility, together with in-general strategies for overall performance enhancement.

7. Conclusions

In this study, energy resilience of district energy systems is comprehensively reviewed to ensure the survivability during extreme events, including concept definition, mathematical quantification, potential threats, and recovery mechanism analysis. In addition to only focusing on energy efficiency or energy robustness for low-impact and high-probability (LIHP) events, the additional consideration of high-impact and low-probability (HILP) events in district energy system planning is quite necessary, to survive power systems when suffering from extreme events (like extreme weather condition, target-oriented destroy in war period). Strategies for energy resilience enhancement can be classified into three types in different phases of extreme events, i.e., resilience preparation in pre-event phase, actions and survivability in on-event phase, and service restoration in post-event phase. Correlation of energy resilience with reliability, robustness, and flexibility in multi-energy systems during the normal period is clarified, together with contradictions and trade-off solutions during the energy system planning, design, and operation stages. Afterwards, an up-to-date approach is proposed to apply energy resilience in district energy communities, systematically considering building energy and urban morphology, electrification and hydrogenation in mobility-based interactive energy sharing systems, and microgrids. Main conclusions are drawn as follows:

1) District energy planning and design based on low-impact and high-probability (LIHP) events fail to ensure survivability in high-impact and low-probability (HILP) events. Energy resilience can enable the system to survive under strong and unexpected disruptions and to recover quickly afterward. However, contradictions between energy resilience and energy efficiency call for trade-off solutions.

2) Types of threat sources are multi-diversified, including infrastructures, operation, data management, government regulation, and policy. In response to different threat sources, mechanisms on system recovery through energy resilience mainly include resilience preparation, fast survivability, and service restoration. Defense measures mainly include natural disaster forecast in resilience-based planning stage, decentralized power supply unit and additional tie switches in resilience-based response stage, and targeted hardening strategy in resilience-based restoration stage.

3) A typology transformation from centralized to distributed energy prosumers was proposed, with step-by-step transition from centralized power plant, prosumer-to-islanded microgrids, prosumer-to-interconnected microgrids, towards distributed energy prosumer. Recent advancement in distributed renewable systems, electric vehicles, peer-to-peer energy sharing, and trading systems can significantly enhance energy resilience of district communities. Furthermore, the development of a regional inter-city energy migration network can promote both urban decarbonization and energy resilience, with the increase in regional renewable energy balance, high renewable penetration in building and transportation sectors.

4) Multi-scale applications of energy resilience in the district energy community with joint and continuous endeavors are necessary, including resilient heating/cooling of buildings, dynamical downscaling for robust design on urban morphology, mobility-based interactive energy sharing in regional districts, and smart microgrids with V2X and energy flexible buildings.

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