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Energy resilience in the built environment: A comprehensive review of concepts, metrics, and strategies

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ABSTRACT

Climate change and its associated extreme weather events pose significant challenges to the built environments, escalating the urgency for improving energy resilience. This study contributes to a systematic understanding of energy resilience in the built environment by addressing four key areas: defining energy resilience, understanding relevant disruptions, quantifying resilience considering all phases, and improving overall resilience. First, this study shows that a universal definition of energy resilience in the built environment is lacking in literature and propose a comprehensive definition that encompasses the resilience's attributes (i.e., vulnerability, resistance, robustness, and recoverability). This study then classifies different types of disruptions that energy resilience seeks to be addressed, with heat wave and component failure events as the most frequently analyzed. Moreover, this study exploits quantitative metrics in five dimensions—Occupants' Metrics, Grid Metrics, Infrastructure Metrics, Economic Metrics, and Hybrid Metrics—used to evaluate energy resilience, while emphasizing the significance of context-specific resilience metrics. Finally, the study reveals gaps for handling resilience in building design/sizing methods and presents resilience enhancement strategies, including design, retrofit, predictive control, and microgrid. For demonstration, this study proposes a framework for assessing and improving building energy resilience, including stakeholder identification, assessing resilience using key performance indicators, determining the scope of resilience, defining events, and exploring improvement solutions.

1. Introduction

Climate change will lead to increased climate variations, which will result in more intense and frequent extreme events [1]. The Intergovernmental Panel on Climate Change (IPCC) predicted that the extreme weather would be more severe and longer than historical ones [2]. The frequency of some extreme events has increased over the past years and more weather-related disasters are anticipated in the future [3]. For example, A Washington Post analysis of data from the National Oceanic and Atmospheric Administration shows that more than 7000 daily temperature records were broken across the United States in the summer of 2022. More than 400 monthly records and 27 historical records were also broken during this third-hottest summer on record [4]. This surge in extreme temperatures is not without precedent. Almost two decades ago, in the scorching summer of 2003, Europe witnessed the death of over 35,000 individuals due to the extreme temperatures [5,6]. The UK observed a peak temperature of 38 °C, and its Health Department estimated that a prolonged heatwave of nine days could result in more than 3000 heat-induced fatalities [7]. Meanwhile, in the Netherlands, temperatures reached as high as 35 °C, contributing to the death of between 1400 and 2200 individuals [8]. These pose a significant threat to both the reliability of the power grid and the well-being of the residents. Heat waves can significantly raise electricity generation costs and demand on the power grid, causing transmission lines and transformers to overheat, resulting in widespread power outages [9]. This presents a challenge to the construction and operation of the grid. On the residential side, extreme weather is usually accompanied by significant associated financial losses with negative impacts on the well-being of residents.

For example, during the first half of February 2021, the winter storm Uri caused an extensive band of frigid air over the center of the United States. Texas declared a "State of Emergency" in 254 Counties Statewide.

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Nomenclature

AC –	Air Conditioning
BES –	Battery Energy Storage
DG –	Diesel Generator
DI –	Discomfort Index
DL –	Durability and Longevity
EEMs –	Energy Efficiency Measures
EENS –	Expected Energy Not Served
EG –	Electric grid
EOD –	Expected Outage Duration
EPS –	Expanded Polystyrene
EPI–	Expected Probability of Interruption
EUI –	Energy Use Intensity
EV –	Electric Vehicle
FL –	Functionality Loss
HadCM3 –	Hadley Climate Model 3
HI –	Heat Index
HR –	Heat Resilience
HRM3 –	Hadley Regional Model 3
HVAC -	Heating, Ventilation, and Air Conditioning
IC –	Imposed Costs
ICT –	Information and Communication Technology
IDO –	Indoor Operating Temperature
IPCC -	Intergovernmental Panel on Climate Change
KPI –	Key Performance Indicator
LEED–	Leadership in Energy and Environmental Design
LST –	Land Surface Temperature
NGPG –	Natural gas power generator
PRISMA–	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PS –	Passive Survivability
PV –	Photovoltaic
RA -	Risk Avoidance
Re –	Resilience Index
ROS –	Rate of Resilience
RR –	Response and Recovery
RS –	Redundant Systems
SOC –	State of Charge
SSSS -	Sub-keyword Synonym Subtopics Searching
UHI –	Urban Heat Island
WWR –	Window-to-wall Ratio

Millions of people were experiencing power outages, and more than 3700 flights were canceled in Houston, Dallas, and other airports. During the extended power outage that followed, there was no electricity to run the heating equipment, and so many buildings became uninhabitable [10].

Furthermore, the resilience of power systems is not only impacted by meteorological events but also by technological advancements and threats like cyber-attacks. Cyber-attacks can disrupt energy systems in numerous ways, including control systems, communication networks, and data storage, leading to loss of control over energy infrastructure and false information being introduced into system operations [11]. This can cause equipment to malfunction, misdirect resources, and potentially result in power outages or incorrect control of building environments.

One of the recent studies emphasizes the importance of improving resilience through local energy resource sharing and integrating the physical and Information and Communication Technology (ICT) layers of power systems. These approaches are crucial for rapidly adapting to changing circumstances and harnessing the potential of technological advances to keep power systems operational during disturbances. The significance of this research lies in its contribution to statistical modeling objectives, as it provides data-driven insights into how power systems can self-organize and alter their physical grid topology to mitigate the effects of widespread outages, thereby improving operational resilience [12]. Additionally, the study by Ghiasi et al. [13] highlights the critical need for understanding and addressing the vulnerabilities of smart grid control systems to cyber-attacks. Their work presents conceptual models that enhance the resilience of power systems by identifying and mitigating potential cyber threats, emphasizing the importance of robust cyber defense mechanisms in maintaining grid stability. Moreover, the research conducted by Ti et al. [14] offers a comprehensive resilience assessment and improvement framework for cyber-physical power systems, particularly under extreme conditions like typhoon disasters. This study underscores the deep coupling between cyber and physical systems in power grids and the necessity of a holistic approach to resilience, combining both information flow and energy flow analysis to ensure system robustness under various disaster scenarios.

The compound impact of extreme climate further stirs an emerging interest from both academia and practitioners to improve and sustain the resilience in the built environment. A clear trend can be observed from the literature published since 1996, as shown in Fig. 1, which plots the number of publications and citations from 1996 to 2023 retrieved from the Web of Science using "resilience", "disruptive", and "building" as keywords. However, there is lacking a holistic defining and understanding of the energy resilience in the built environment. Therefore, it is crucial to review the present state of the art and summarize the work performed and identify the research gaps that can be addressed in the future.

The novelty of this study lies in presenting a comprehensive framework for understanding and enhancing energy resilience in the built environment, addressing the increasing risks posed by climate-related extreme weather events. This study contributes by systematically defining energy resilience, categorizing disruptive events into climatological, meteorological, and technology malfunction events, and proposing new resilience metrics that provide a holistic assessment. Specifically, we introduce a hybrid metric called "Effectiveness of Resilience Resources," which evaluates key factors like Accessibility, Usability, Sufficiency, and Operability, thereby filling an existing gap in resilience evaluation of the built environment. Additionally, the study innovates by developing a practical five-step framework for resilience enhancement, encompassing stakeholder identification, resilience scope definition, disruption classification, key performance indicator evaluation, and tailored resilience improvement strategies. The proposed methodology and framework aim to enhance both the robustness and adaptability of buildings by incorporating advanced predictive control, retrofitting, and micro-grid solutions, ensuring a resilient built environment that can withstand multiple types of disruptions.

There exist four critical gaps in the existing literature on energy resilience in the built environment. Literature review methodology and statistics will be elaborated in section 2. These gaps highlight the need for further research for developing effective strategies and policies to enhance and evaluate resilience in the built environment.

The first gap is about the universal definition of energy resilience in the built environment. It is crucial for academia and practitioners to work towards developing a consistent and comprehensive definition of energy resilience, considering various factors that contribute to it, such as technical, economic, social, and environmental aspects. Addressing this gap will lead to a more holistic understanding of energy resilience and help guide future research and policy development in this area.

The second gap is on understanding clearly what energy resilience is against. A clear understanding of the various disruptions that energy

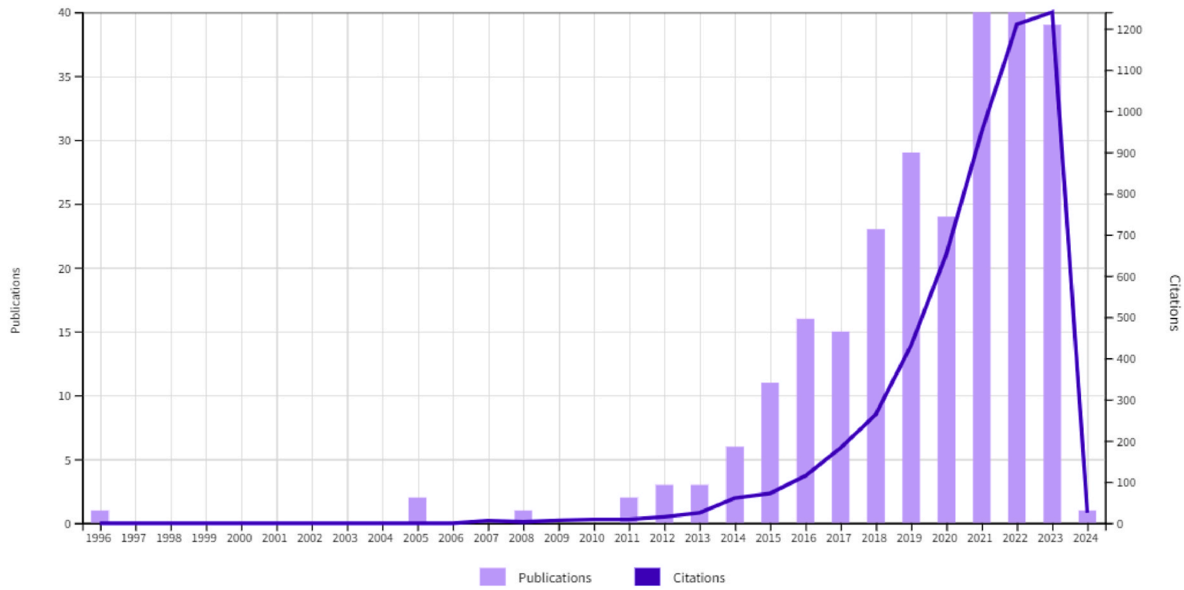

Fig. 1. Number of publications and citations from 1996 to 2023 retrieved from the Web of Science using "resilience", "disruptive", and "building" as keywords.

resilience in the built environment aims to address is necessary. This involves defining, identifying, and classifying different types of disruptions, as well as evaluating their impacts on various parts or levels of the built environment. By understanding the specific threats and challenges that energy resilience seeks to address, academia and practitioners can develop more targeted and effective strategies for enhancing resilience.

The third gap is on how to evaluate the energy resilience. It is essential to acknowledge that different building types, communities, and energy systems may have unique needs and vulnerabilities by themselves, so metrics used to evaluate energy resilience are depending on the specific context. Additionally, it is necessary to involve key stakeholders in the evaluation process, such as building owners, policymakers, and community members, ensuring that the adopted metrics are relevant and meaningful to different stakeholders. This gap highlights the need to exploit how to quantify the benefits of various resilience approaches and develop context-specific evaluation metrics.

The fourth gap is on how to improve energy resilience. A critical question to be tackled is whether the design and sizing methods provide sufficient resilience capacity for buildings and energy systems. It is essential to identify the gaps and develop strategies to bridge those gaps. This may involve investigating innovative design approaches, technologies, and policies that enhance resilience while considering the unique characteristics and vulnerabilities of each built environment context (e.g., more roof insulation and using solar control window film, integrating photovoltaic and battery system, and modifying operating strategies).

This study will aim to address four identified research gaps related to energy resilience in the built environment, focusing on four specific perspectives, with the goal of contributing to a more comprehensive understanding of energy resilience. The objective of this study is to first develop a consistent and comprehensive definition of energy resilience in the built environment will lead to a more holistic understanding of the concept. This will allow research community and practitioners to communicate more effectively, compare results across different studies, and identify literature gaps that warrant further investigations. Secondly, by defining, identifying, and classifying various disruptions, academia and practitioners can develop more targeted and effective strategies to enhance energy resilience. This will help ensure that the most pressing threats and challenges faced by buildings and energy systems in the era of climate change are appropriately addressed, resulting in more resilient communities and infrastructure. Thirdly, context-specific resilience metrics can be developed by acknowledging the unique needs and vulnerabilities of different building types, communities, and energy systems and involving key stakeholders in the evaluation process. This will enable more accurate and meaningful assessments of energy resilience, leading to better-informed decisions and policy development. Lastly, investigating and addressing the gaps in design and sizing methods will promote the development of innovative design approaches, technologies, and policies that enhance resilience. This will help ensure that the built environment is better equipped to withstand and recover from disruptions, ultimately contributing to more resilient and sustainable communities.

The rest of this study is organized as shown in Fig. 2. Section 2 details our systematic literature review methodology. Section 3 summarizes the literature review results of concepts of resilience, types of events related with resilience, metrics used to evaluate resilience, and how to improve resilience. Section 4 proposes a framework to evaluate and improve building resilience. Section 5 concludes this review work.

2. Methodology

How to holistically and unbiasedly search and identify the relevant papers for the literature review is crucial. Most of the review papers on the energy resilience research topic did not describe the methods or keywords they used to search or collect papers [15–17]. Some review papers started with a first round of searches using certain keywords, and then additional searches were conducted using the keywords of the first round of papers [18].

We use the Sub-keyword Synonym Subtopics Searching (SSSS) engine to search for relevant publications [19]. This is a systematic search

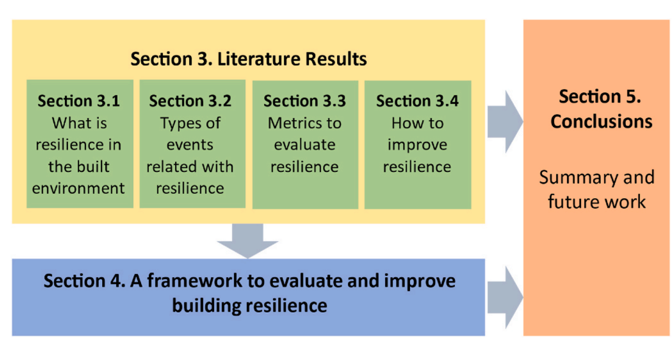

Fig. 2. Content organization diagram of this study.

methodology to capture the most important literature. It exhausts relevant papers by multiple searches with synonym sub-keywords.

In this study, we use keywords that consist of three sub-keywords lists. The first sub-keyword narrows the paper to focus on energy resilience. The full list of the first sub-keyword is: “energy resilience,” “thermal resilience,” “energy availability”, and “energy robustness.” The second sub-keyword defines energy resilience against disruptions. The full list of the second sub-keyword is: “disruptive event,” “extreme climate event,” and “power failure.” The third sub-keyword defines the scope and focus of this study is on the built environment. The third sub-keyword is: “in buildings,” “HVAC,” “in building environment,” and “in built environment.” Google Scholar is the primary search engine for this study, and the full list of search terms in Google Scholar is a complete combination of each sub-keyword. An example of searching keywords combination is “energy resilience,” “disruptive event,” “in built environment.” The total number of searching keyword combinations in this study is $4\times3\times4 = 48$ keyword combinations. The citation threshold, the number of papers per search, and the year of publication range are defined as follows: including the first 10 papers per search; the year of publication ranges from 2010 to 2023; and the citation threshold is set at 5 for papers from 2010 to 2022, and 0 for papers from 2020 to 2023. Table 1 summarizes the parameters of SSSS methodology used in this study.

The total number of searched papers is 357 after eliminating the duplicated ones. We carefully reviewed the extracted 357 papers and selected 104 papers based on expert domain knowledge for this study. These 104 remaining papers were then summarized in a Table that is available from a public website (https://github.com/Annex-82-A1/building-resilience-review), which includes a brief summary, and evaluations of each paper in terms of disruptive event, disruptive event category, resilience scope/level, the definition for resilience, method type, resilience-related key performance indicators (KPIs), KPI formula/definition, stakeholders, and resilience strategy. Fig. 3 illustrates the profile of the reviewed paper by publication sources and the number of papers per year from 2010 to 2023.

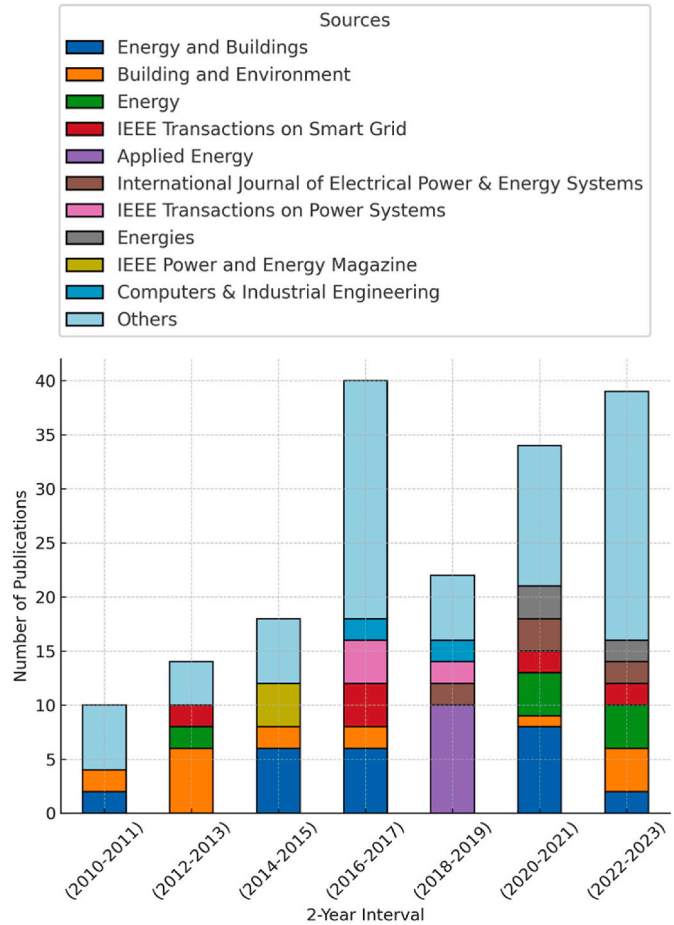

Fig. 3. Profile of the reviewed paper by publication source and year.

3. Concepts, metrics, and strategies

3.1. What is resilience?

The concept of resilience is first introduced by Holling in the field of the ecological system, and this concept was used to describe the persistence of the ecosystem against fluctuations [20]. In recent years, resilience has been broadly applied to many other fields as well, including building retrofit [21,22], comfort and health [23,24], micro-grid power systems [25], power grid [26], etc.

Different studies and reports have used varying definitions and metrics to measure energy resilience. Of all the literature reviewed, recoverability and resilience are the two most important aspects considered when defining resilience. There are some studies that focus more on the recoverability aspect when defining the resilience [17,27–30]. On the contrary, some other studies focus on the aspect of resistance when defining resilience [31–41]. Moreover, there are also studies that define resilience with an emphasis on both recoverability and resistance [42–57].

However, there is a gap in the literature regarding a universal definition of energy resilience in the built environment. This lack of a universal definition makes it difficult to compare and integrate findings across different research areas, thus making it a challenge to identify best practices and develop consistent policies and guidelines for improving energy resilience in the built environment.

Thus, in this study, energy resilience in the built environment is referred to as the inherent and adaptive capacity of buildings, infrastructure, and urban energy systems to anticipate, absorb, recover from, and adaptively respond to disruptions in energy supply and demand, while ensuring sustained functionality, efficiency, and equitability both in the short and long term.

Energy resilience features multiple phases which can be described as "resilience trapezoid" and "resilience triangle" [17,58,59]. Fig. 4 outlines the stages a building or system undergoes after experiencing a disruptive event. Between time t_0 and t_1, the system operates at its normal performance level. The disruptive event occurs at t_1, causing the system performance to degrade during "Disruption Stage 1″ until it reaches its lowest performance level at time t_2. This point, referred to as the "degraded level" in the figure, signifies the worst performance experienced by the system. In the "resilience triangle" concept, the system immediately starts to recover at the end of "Disruption Stage 1″, eliminating the need for a "Disruption Stage 2″ The "Final State" stage follows directly after "Disruption Stage 1″ as the system gradually returns to its

Table 1
Parameters of Sub-keyword Synonym Subtopics Searching (SSSS) for paper search in this study.

Parameter		Values
Sub-keyword 1		energy resilience, thermal resilience, energy availability, energy robustness
Sub-keyword 2		disruptive event, extreme climate event, power failure
Sub-keyword 3		in buildings, HVAC, in building environment, in built environment
Year from	2010	2020
Year to	2022	2023
Citation threshold	5	0
Number of papers per search	10	10

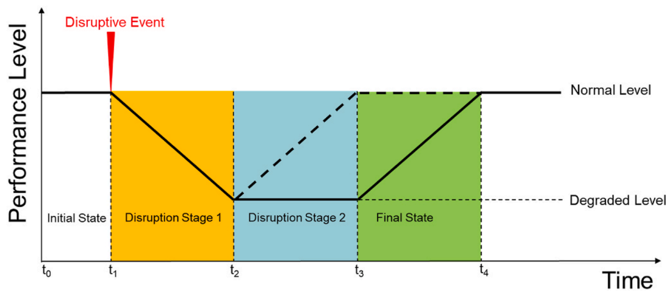

Fig. 4. Resilience "trapezoid".

pre-disturbance condition. However, in the "resilience trapezoid" concept, there is no immediate recovery action taken at the end of "Disruption Stage 1″ This results in a constant degraded performance level during "Disruption Stage 2."

The resilience trapezoid concept not only describes the general process a building or system undergoes during a disruptive event but can also be used to define or calculate resilience-related metrics. These metrics and their applications will be discussed with greater detail in Section 3.3: How to Evaluate Resilience.

3.2. Types of events related with resilience

Energy resilience in the built environment is essential to ensure that buildings and infrastructure can withstand and recover quickly from all types of damage or disruption. Understanding the similarities and differences between these disruptions is critical to developing an effective energy resilience strategy. This knowledge can guide the development of measures to reduce the risks associated with these disruptions and ultimately protect critical infrastructure and services.

This section begins with an overview of the major events that often lead to energy disruptions and security degradation, based on identified literature. A high level of energy resilience typically implies a strong ability to withstand the effects of an energy disruption or shortage and quickly restore or maintain normal building operations and services [60]. Energy disruptions include a range of events or incidents that adversely affect the normal operation of energy systems and infrastructure. These disruptions can result from natural hazards, power outages, and climate change [61], as well as other causes such as cyber-attacks. Understanding the nuances of these disruptions and their consequences allows different stakeholders to take a targeted approach to improving energy resilience. For example, enhancing the performance of the building envelope has been shown to be more effective and feasible in improving resilience to long-term shifts in global temperature and increasingly frequent heat waves at the building level [42,62]. However, during a random power outage of any length, active measures such as on-site generators, PV/battery storage systems are generally required to maintain safe conditions and increase the probability of survival [62,63]. Advancing energy resilience of the built environment plays an important role in maintaining the functionality and safety of buildings and infrastructure during disruptive events. Therefore, by understanding the complexity of different disruptive events, stakeholders can develop and implement targeted strategies to mitigate risk and improve energy resilience, ultimately protecting critical infrastructure and building services.

In previous studies on the built environment, resilience assessments have focused on the ability of the built environment to maintain an acceptable level of functionality during and after a disruptive event and to return to the full functionality within a given time frame. Fig. 5 summarizes the disruptive events studied in the collected literature and is plotted at two-year intervals from 2010 to 2023. Common disruptive events to which a built environment is vulnerable include natural disasters (heat waves, floods, hurricanes/typhoons, winter storms, wildfires, etc.) and technology malfunctions and failures (such as grid failures). The overall trend shows that the number of studies on energy resilience has increased almost every year since 2015, indicating the importance of this research topic. Since the literature review has not been extended to the end of 2023, the number of studies from 2023 is approaching and is likely to be in excess of the total literature from 2021 to 2022.

In particular, the classification of disruptive events is a complex task due to the inter-correlation of the causes of the events. While individual extreme weather events, such as heatwaves, can have a variety of causes and are typically studied in the field of meteorology, the overall trend of increasing frequency and intensity of heatwaves is a clear signal of ongoing global climate change. Therefore, to avoid the confusion and provide clear insights, the classification of disruptive events used was determined by whether a particular event was mentioned in the literature. For example, the category "Global temperature rise" refers to long-term changes in global temperature [64], so a paper that discusses resilience to global warming (e.g., under future climate scenarios) is categorized into this type. The "Heat waves" category refers to short-term heatwave events, and papers in this category focus on one-off heatwave events. It is worth noting that in the collected literature, "Component failure" occur mainly due to the system failures alone (such as age-related or random equipment failures) or triggered by extreme events (such as heatwaves and winter storms), so both are counted in this category.

As shown in the pie chart of Fig. 5, studies on cases such as component failures, heatwaves, and global temperature rise that have a direct impact on the built environment are the most popular with a relatively high publication number, accounting for more than 60 % of the total literature collected. The same trend can be seen in the bar chart, with these studies accounting for more than half of the annual publications since 2012. In addition, some of the literature reviewed [49,63,65] did not focus on or even never mentioned specific types of disruptive

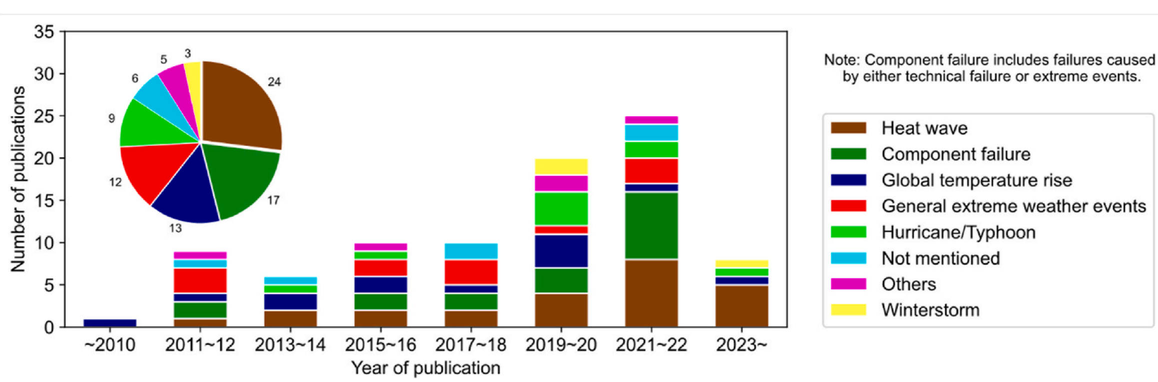

Fig. 5. Publications on different disruptive events by year.

events, but instead proposed general solutions and assessment methods for common extreme weather events. For these studies, we categorize them accordingly as "General extreme weather events" or "Not mentioned". Besides. the "Other" category mainly includes relatively rare events, such as tsunamis [32] and earthquakes [66]; although they are beyond the scope of this study's focus on energy resilience in the built environment, they inform this work both methodologically and definitionally. Therefore, this type of literature is included in the bibliographic statistics but is not discussed in depth in this section.

Based on the different types of disruptive events, the cases reviewed in the literature can be grouped into the following three main categories. As shown in Fig. 6, based on the collected references focusing on building and infrastructure energy resilience, three types of disruptive events are proposed, namely, climatological event, meteorological event, and technology malfunction event.

- **Climatological event**: Climatological disasters are natural disasters that result from long-term weather patterns and climate anomalies. They typically involve extreme temperature or precipitation events that persist over an extended period of time. These disasters can have widespread and severe impacts on infrastructure, building operations, and ultimately human life. A typical example of climatological disasters is long-term climate change, such as more frequent El Niño and La Niña events [67].
- **Meteorological event**: Meteorological disasters are natural catastrophes that result from extreme weather events and atmospheric disturbances. These disasters are primarily caused by atmospheric processes and are studied within the field of meteorology. Meteorological catastrophes can have a significant impact on human life, property, and the environment. Some examples of meteorological disasters are heat wave, winter storm and thunderstorms. 2003 European heatwave [68] and 2021 Texas winter storm Uri [69] bringing people's attention to how to efficiently and effectively handle such short-time scale disruptive events.
- **Technology malfunction event**: Technology malfunction can be random or due to aging equipment and occurs when there is a loss of electrical power in a given area. The impact can range from small, localized outages that affect a few homes or businesses to large-scale blackouts that affect entire cities or regions. It should be noted that technology malfunctions are not considered meteorological or climatological catastrophes, but they can be triggered by events in these categories and increase the threat level.
- **Others**: Other events that affect resilience are included in the "Other" category, such as tsunamis [28], resource capacity, pandemics [17], etc. Since the solutions to these events are methodologically and definitionally relevant to this work, they are included in the bibliographic statistics, but will not be explored in depth because they are beyond the scope of this study focusing on the energy perspective.

Fig. 6 shows the number of different categories of disruptions covered in the collected literature, as well as specific cases. For cases where a general terminology is used, or a broad solution is proposed that is not event-specific such as in Refs. [70,71], we use "Not mentioned" to classify them. It can be seen that in the previous literature, disruptive events on meteorological disturbances were the most studied, followed by climatological and technology malfunction disturbances. Specifically, for energy resilience against disruptions, most studies focused on global temperature rise [72], heat waves [73], general extreme weather events [63], and component failures [21]. This actually is strongly reflecting the theme of energy resilience in the built environment, since climate change directly affects the building energy consumptions as well as the indoor environment; and how to ensure that buildings provide normal services under these circumstances is the main theme of most research on energy resilience.

However, compared to heat waves and global temperature rise, there are few case studies on cases such as hurricanes and tsunamis [32,74]. This may be due to differences in the nature of the events and the ability to effectively respond at the building scale. The main difference between climatological and meteorological is the time scale. Briefly, climatology focuses on the long-term trends in climate patterns, while meteorology focuses on the short-term changes in weather patterns. The two will have different solutions for improving energy resilience. Enhancing the performance of the building envelope will increase energy resilience to climatological disruptive events, such as resistance to annual temperature increases. However, to improve resilience to meteorological hazards such as typhoons or floods, the use of backup generators or batteries can better help ensure efficient building operation during power outages. For example, Larsen and Filippín [62] discussed how to improve the energy resilience of buildings to cope with a progressively warmer future climate from a climatological perspective. The study proposed solutions such as increasing the thermal insulation of the building envelope and improving building performance in the initial design phase. From a meteorological perspective, Sepúlveda and Hegedus [63] investigated the use of microgrids with photovoltaic, wind, and battery power to ensure normal building operations during power outages caused by occasional extreme weather events. In addition, the energy resilience metrics for meteorological and climatological events are also different, which will be discussed in detail in the Resilience Metrics section.

It is worth noting that both technology malfunctions (e.g., aging and random equipment failures) and meteorological events (e.g., old buildings or equipment capacity unable to cope with temperature rise during heatwaves) can cause system failures and subsequent power instability; the cumulative effect of two disruptions also cannot be ignored. For example, some studies discussed the situation where the failure of air conditioning coincided with a hot weather event (referred to as a heat disaster) in which the health and well-being of occupants are severely compromised [75]. A single perspective, such as simply increasing the performance of the building envelope, does not always meet the level of resilience to randomly occurring component failures; adding backup power and fuel is also seen as a viable way to increase the resilience level [29]. Therefore, the occurrence of component failures is included in both the meteorological and technology malfunction categories and should be considered not only by building owners but also by city

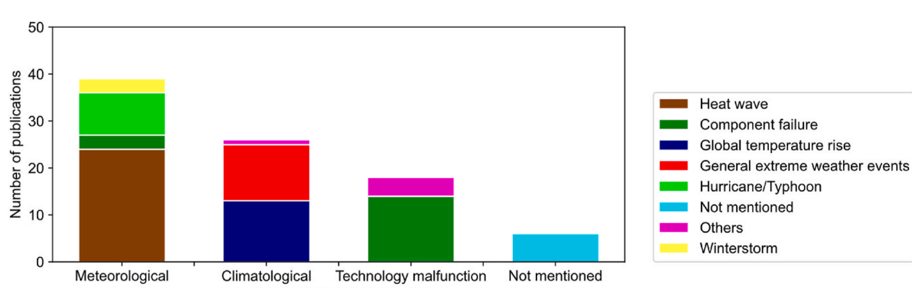

Fig. 6. Publications grouped by Disruptive Event Category.

planners.

In addition to equipment failure and natural disasters, cyber-attacks are another major cause of power outages. Cyber-attacks are increasingly targeting the building and energy sectors, especially as energy devices and digital infrastructure become more interconnected [11,76]. Cyber-attacks can disrupt energy systems in a number of ways. They can target control systems, communication networks, or data storage, resulting in a loss of control over energy infrastructure [75]. They can also introduce false information into system operations, causing equipment to malfunction or misdirecting resources, which could lead to power outages or incorrect control of building environments. In some cases, sophisticated cyberattacks could cause physical damage to energy infrastructure, similar to the effects of natural disasters or equipment failures [17]. There is a growing need to protect energy systems from cyber threats, which is becoming an important aspect of energy resilience. Efforts to improve energy resilience in the built environment through enhanced cybersecurity measures represent a separate and large research direction and are beyond the objectives of this study, so they will not be addressed in detail in this study but are worthy of the reader's attention.

3.3. Metrics to evaluate resilience

Despite growing awareness of resilience in the built environment, a universal, comprehensive metric for its evaluation remains absent, often leading to a fragmented understanding that focuses on individual aspects such as thermal comfort or energy efficiency. This issue is exacerbated by the diverse range of building types and urban configurations, resulting in an array of metrics and KPIs that complicate cross-research comparison and integration. Furthermore, existing metrics are lacking adaptability to various scales, which limits the development and implementation of effective resilience strategies. In response to this research gap, this study systematically analyzes quantitative metrics suitable for buildings, categorizes quantitative metrics into five groups, explores their relationships, and proposes a guiding flowchart for practitioners. This approach aims to create adaptable and effective resilience strategies for a broad spectrum of building types, urban configurations, and climate scenarios.

The lack of universally accepted methods for evaluating energy resilience in the built environment has led to the use of various metrics and KPIs across different studies and reports. In the context of quantitative analysis, several possible metrics, as listed below, can be employed to assess energy resilience in buildings, communities, and energy systems, taking into account their unique needs and vulnerabilities.

- **Occupants' Metrics**: These metrics focus on occupant comfort and safety, including measures such as the unmet degree hour, heat index, and hazard level [21,34,41,62,77,78]. These quantitative indicators can help evaluate the effectiveness of resilience strategies in protecting occupants from the impacts of extreme heat events.
- **Grid Metrics**: These metrics assess the resilience of energy systems by evaluating the frequency and duration of power outages [17,79]. By analyzing these factors, it is possible to identify areas of vulnerability and opportunities for improvement in the energy system.
- **Infrastructure Metrics**: Focusing on the physical aspects of energy resilience, these metrics consider the condition of energy infrastructure, the availability of backup generators and other emergency equipment, and the capacity of the energy system to withstand disruptions [17,35,80]. These indicators can help prioritize investments in infrastructure upgrades and improvements.
- **Economic Metrics**: These metrics examine the economic impact of energy disruptions, including the cost of energy disruptions and the impact of power outages on businesses and households [29,35,81]. By understanding the economic consequences of energy resilience, stakeholders can better allocate resources and prioritize resilience strategies.
- **Hybrid Metrics**: Combining multiple metrics from different areas, hybrid metrics provide a more holistic view of energy resilience, capturing the complex interplay between various factors that contribute to a resilient built environment. Henry et al. [29] proposed a hybrid metric called effectiveness of a resilience resource. This hybrid metric assesses the overall effectiveness of a resilience resource by considering its Accessibility (A), Usability (U), Sufficiency (S), and Operability (O). It considers these factors equally important, assigning them values between 0 and 1, and multiplying them to determine the effectiveness score. The inclusion of operability also acknowledges the role of human intervention in triggering or linking the resource and system. Another hybrid resilience metric is proposed by Nan and Sansavini [31], this hybrid metric offers a comprehensive view of system resilience by incorporating measures of both resilience (Robustness, Recovery Speed, and Recovery Ability) and vulnerability (Performance Loss and Loss Speed). The integrated metric does not assign any weighting factors to these individual measures, treating them as equally influential on the overall resilience. This assumption may make the metric more robust against bias, but also implies that all the measures are equally important in all situations, which may not be true in some scenarios.

It is crucial to involve key stakeholders in the evaluation process, such as building owners, policymakers, and community members, to ensure that the metrics used are relevant and meaningful. By employing a quantitative approach tailored to the specific context, academia and practitioners can effectively compare and integrate findings across research in the built environment. We have collected a total of 44 quantitative metrics from the reviewed works. These metrics have been grouped into the five categories proposed earlier, as shown in Fig. 7: Occupants' Metrics, Grid Metrics, Infrastructure Metrics, Economic Metrics, and Hybrid Metrics.

Fig. 7 shows that 31.8 % of the reviewed metrics were Occupants' Metrics, 18.2 % were Grid Metrics, 31.8 % were Infrastructure Metrics, 13.6 % were Economic Metrics, and the remaining 4.5 % were Hybrid Metrics. It is evident that Occupants' Metrics and Infrastructure Metrics are the most popular and widely used metrics in evaluating energy resilience in the built environment in this study. While the metrics are organized into the previously mentioned five categories, it's essential to recognize the inherent overlaps and cascade effects among these categories. For example, an increase in the infrastructure metric, such as "functionality loss", might simultaneously lead to a change in occupant metrics, like an increased value for "discomfort index". However, it is challenging to draw such a clear boundary among different metrics.

Occupants' Metrics directly address the impact of energy resilience

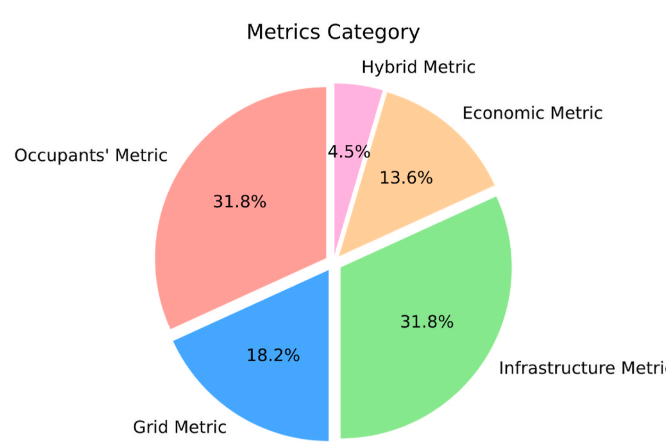

Fig. 7. Resilience Metric category pie chart.

strategies on the comfort, health, productivity, and safety of building occupants. These metrics are crucial in evaluating the success of resilience measures, as the primary goal of creating a resilient built environment is to protect and ensure the well-being of the people who live and work in these spaces. Some representative occupant metrics from the literature are listed in Table 2:

Infrastructure Metrics focus on the physical aspects of energy resilience, assessing the condition and capacity of energy infrastructure, as well as the availability of backup generators and other emergency equipment. These metrics are essential in identifying vulnerabilities and opportunities for resilience improvement within the built environment, ultimately contributing to the development of robust and adaptable resilience strategies. Some examples of quantitative infrastructure metrics, together with calculation formulas are listed in Table 3.

The popularity of these two categories of metrics highlights the importance of prioritizing human well-being and the physical robustness of infrastructure when evaluating energy resilience in the built environment. By concentrating on these aspects, academia and practitioners can effectively design and implement measures that safeguard the health and safety of building occupants while also strengthening the overall resilience of buildings and urban systems.

While Occupants' Metrics and Infrastructure Metrics are more prevalent in the current evaluation of energy resilience in the built environment, Grid Metrics and Economic Metrics are also essential components that should not be overlooked. These metrics provide valuable insights into the impacts of energy disruptions on the power grid and the broader economy.

Grid Metrics assess the resilience of energy systems by evaluating factors such as the frequency, duration, and extent of power outages. These metrics help identify areas of vulnerability within the energy grid and can guide investments in infrastructure improvements and emergency response planning. Some examples of Grid Metrics are listed in Table 4.

Economic Metrics examine the economic impacts of energy disruptions, including the cost of energy disruptions and the economic consequences of power outages on businesses and households. By understanding the financial implications of energy resilience, stakeholders can better allocate resources and prioritize resilience strategies. Some examples of Economic Metrics are listed in Table 5:

By incorporating Grid Metrics and Economic Metrics into the evaluation of energy resilience, academia and practitioners can gain a more comprehensive understanding of the challenges and opportunities associated with creating a resilient built environment. This holistic approach will ultimately contribute to the development of more effective and robust resilience strategies that address a broader range of concerns and stakeholder needs.

The formulas and variables involved in these metrics have been sorted and examined, with key parameters such as time, system performance level, the temperature during normal operation conditions, the temperature during disruptive events, various types of costs, power/load during disruptive events, power/load during normal operation conditions, loss, onsite power generation, EV state of charge (SOC),

Table 2
Representative occupants' metrics.

Metric Name	Definition	Formula	Terms	Ref
Passive Survivability Index (PSI)	This metric assesses the ability of a building to maintain habitable conditions during a power outage or extreme weather event without relying on active mechanical systems.	$\mathrm{PSI} = t_{threshold} - t_{failure}$	$t_{threshold}$: the time when temperature reaches threshold. $t_{failure}$: the time when the power failure occurs	[60] [82]
Heat Index (HI)	The heat index combines air temperature and relative humidity to determine an "apparent temperature," which represents how hot the conditions feel to the human body. A higher heat index indicates a higher risk of heat-related illnesses.	$HI = -8.785 + 1.611394 11T + 2.338549RH - 0.14611605\,(T \bullet RH) - 0.012308094T^2 - 0.016424828RH^2 + 0.002211732T^2 \bullet RH + 0.00072546T \bullet RH^2 - 0.000003582T^2 \bullet RH^2$	T: the air temperature RH: the relative humidity	[62, 77]
Indoor Overheating Degree (IOD)	This metric evaluates the risk of indoor overheating by considering both the intensity and frequency of temperature exceedance in various zones of a dwelling, accounting for diverse thermal comfort limits and occupant behaviors	$IOD = \frac{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ(z)}}\left[\left(T_{in,o,z,i} - T_{comf,z,i}\right)^{+} \bullet t_{i,z}\right]}{\sum_{z=1}^{Z}\sum_{i=1}^{N_{occ}} t_{i,z}]}$	$T_{in,o,z,i}$: the zone indoor operative temperature $T_{comf,z,i}$: the zonal thermal comfort limit N_{occ}: the total number of zonal occupied hours t: the time step z: the total number of building zones	[77] [83]
Climate Change Amplification Factor	This metric quantifies the increase in indoor temperatures due to outdoor temperature rise, helping to identify the potential for increased discomfort or health risks in the future.	$C_{T_{mean}} = \frac{\delta T_{mean}^{internal}}{\delta T_{mean}^{external}}$ $C_{T_{max}} = \frac{\delta T_{max}^{internal}}{\delta T_{max}^{external}}$	$\delta T_{mean}^{internal}$: the change of mean temperature observed within the building $\delta T_{mean}^{external}$: the change of mean temperature observed in the weather file $\delta T_{max}^{internal}$: the change of max temperature observed within the building $\delta T_{max}^{external}$: the change of max temperature observed in the weather file	[84]
Discomfort Index (DI)	The discomfort index combines temperature and humidity variables to assess the level of thermal discomfort experienced by occupants, guiding the implementation of appropriate resilience measures.	$DI = \frac{T_{wb} + T_a}{2}$	T_{wb}: the wet-bulb air temperature T_a: the dry-bulb air temperature	[75]

Table 3
Representative infrastructure metrics.

Metric Name	Definition	Formula	Terms	Ref
Resilience of a System	This metric quantifies the resilience of a system to be the ratio of recovery at reference time to loss suffered by the system at some previous time.	$R(t_r) = \frac{\varphi(t_r) - \varphi(t_d)}{\varphi(t_0) - \varphi(t_d)}$	$\varphi(t_r)$: the system performance level at the reference time $\varphi(t_d)$: the system performance level at the degraded stage $\varphi(t_0)$: the system performance level before the disruptive event	[29]
Resilience Time	This metric measures the duration of time required for an energy system to recover to certain level after a disruption.	$T_R = \sum_{i=1}^{n} T_i$	T_i: the time elements	[29]
Functionality Loss (FL)	This metric evaluates the decrease in performance or functionality of an energy system during a disruptive event.	$FL = \int_{t_0}^{t_0+T_{IP}} [f_{desired}(t) - f_{actual}(t)] \bullet dt$	$f_{desired}$: the desired system functionality f_{actual}: the actual system functionality	[35]
Robustness	This metric assesses the ability of an energy system to withstand the impacts of a disruptive event without experiencing significant degradation in performance or functionality.	$R = min(MOP(t))$	MOP: the measurement of performance t_d: the disruptive phase start time	[31, 85]
Rapidity	This metric evaluates the speed at which an energy system can recover its normal operation after a disruption	$RAPI_{DP} = \frac{MOP(t_d) - MOP(t_r)}{t_r - t_d}$	t_r: the recovery phase start time t_{ns}: the new steady-state phase start time	[31]
Recovery Ability (RA)	This metric measures the capacity of an energy system to restore its functionality and performance after a disruptive event.	$RA = \left\lvert \frac{MOP(t_{ns}) - MOP(t_r)}{MOP(t_o) - MOP(t_r)} \right\rvert$	t_o: the original steady-state phase	[31]

battery SOC, relative humidity, and power outage duration time playing significant roles in the calculation of these metrics. The occurrence numbers for those key variables in this review are presented in Fig. 8.

Among all the variables involved in the computation of resilience metrics, time emerges as the predominant factor, followed closely by the system performance level. Additionally, temperatures during both normal and disruptive events are frequently employed in these calculations. These four parameters represent the most commonly utilized variables in resilience metric analysis, signifying their critical role in evaluating system robustness and adaptability. Time is a fundamental variable used in resilience metrics, as it allows us to track the system's response and recovery during and after disruptive events. By monitoring the system over time, we can analyze its ability to withstand disruptions, adapt to changing conditions, and recover from disturbances. The system performance level serves as an indicator of the system's overall efficiency and effectiveness. In the context of resilience, a high-performance system is more likely to better cope with disruptions and recover quickly. By analyzing the system performance level, we can identify areas for improvement that will enhance the system's resilience. Monitoring the room air temperature during normal operations and disruptive conditions helps assess the system's resilience. By monitoring temperatures during these events, we can evaluate the system's ability to cope with and recover from disruptions, thus providing insights into its resilience.

In addition to the metrics we have already discussed, it is also essential to consider the framework proposed in the study [86], which emphasizes the critical role of energy delivery in the resilience of the built environment. This study proposed a robust design approach for the energy capacity of buildings, focusing on the integration of on-site renewable sources like photovoltaic panels coupled with storage batteries. The resilience of such systems was characterized by metrics such as "robustness," "redundancy," "resourcefulness," and "rapidity," alongside sustainability metrics like self-reliance and intergenerational equity enhancement. Their approach underscored the increasing importance of on-site energy generation and storage capabilities in enhancing the robustness of the building energy supply, especially in the face of natural hazard events such as hurricanes and earthquakes. This perspective is well aligned with other studies [29,31,85] on the significance, particularly regarding the capacity of energy systems to withstand disruptions. Furthermore, the study's emphasis on "recovery and adaptability" during and after events that disrupt civil infrastructure services resonates with the proposed categorization of resilience metrics. It reinforces the need for a comprehensive evaluation framework that not only considers the immediate impacts of disruptions but also the long-term adaptability and sustainability of energy systems in the built environment.

Additionally, the study by Deng et al. [87] introduced a novel approach to assessing the resilience of urban distribution networks, particularly in the context of extreme heat wave events. This study proposed an energy management method and a performance assessment index based on prioritized power consumption. By coordinating various peak shifting and averting management measures, the study effectively maximized power supply during extreme weather conditions. The

Table 4
Representative grid metrics.

Metric Name	Definition	Formula	Terms	Ref
Load curtailment	This metric evaluates the reduction in electrical demand during a power outage, often as a result of demand-side management strategies or energy conservation measures. Load curtailment can help alleviate the strain on the energy system and expedite the recovery process.	$Cur_{m,t}^{EL} = \left[D_{m,t}^{EL} - P_{m,t}^{CG} - P_{m,t}^{RE} + \left[\sum_{j \in N_m} P_{j,t}^{EV}\right]^{-}\right]^{+}$	$Cur_{m,t}^{EL}$: the essential load curtailment at microgrid m and time t $D_{m,t}^{EL}$: the essential demand of microgrid m at time t $P_{m,t}^{CG}$: the controllable generation power at microgrid m at time t $P_{m,t}^{RE}$: the renewable energy sources power at microgrid m at time t $P_{j,t}^{EV}$: the electric vehicle power at time t	[51]
Rate of resilience (ROS)	This metric quantifies the speed at which the energy system recovers from a disruption, indicating the system's ability to restore service to affected customers quickly.	$ROS = \frac{C_{max}}{L_r}$	C_{max}: the resilience capacity L_r: the recovery time	[17]

Table 5
Representative economic metrics.

Metric Name	Definition	Formula	Terms	Ref
Resilience Index (Re)	This metric calculates the relative percentage between the maximum possible imposed costs (IC) during an energy disruption and the actual imposed costs in the failure mode. A higher resilience index indicates that the energy system is better equipped to minimize the economic impact of disruptions.	$Re_{i,j} = \frac{IC_i^{Max} - IC_{i,j}}{IC_i^{Max}}$	IC_i^{Max}: the maximum possible imposed cost $IC_{i,j}$: the imposed cost	[35]
Imposed Cost (IC)	This metric measures the direct and indirect costs imposed on the energy system, businesses, and households due to energy disruptions. Imposed costs can include lost revenue, increased expenses, and the cost of emergency response efforts. By assessing imposed costs, stakeholders can better understand the economic consequences of energy disruptions and prioritize resilience strategies that mitigate these impacts.	$IC_{i,j} = \left[OC_{i,j} + \sum_{k=1}^{K} \left(FL_{i,j,k} \bullet PC_{i,k}\right)\right] - OC_{i,desired}$	$OC_{i,j}$: the operational costs during failure mode j and time period i K: the total number of system functional services $PC_{i,k}$: the penalty costs $OC_{i,desired}$: the operational cost for uninterrupted system running optimally during time period i $FL_{i,j,k}$: the functional service loss	[35]

resilience assessment index, defined as the ratio of the total amount of load after intra-day scheduling in extreme weather to the total amount of load predicted by the system, provided a quantitative measure of the system's resilience. This index offers a visual reflection of the power supply capacity of the system in extreme weather, with a higher value indicating greater system stability and resilience [87]. This approach of resilience assessment is consistent with other study [35] as it provides a practical and quantifiable method to evaluate the effectiveness of resilience strategies in mitigating the impacts of extreme heat events on energy systems.

Furthermore, the systematic review conducted by Houghton and Castillo-Salgado [88] provided valuable insights into the role of green building design strategies in enhancing community health resilience to extreme heat events. Their study, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) method, evaluated the effectiveness of Leadership in Energy and Environmental Design (LEED) credit requirements in reducing the adverse effects of extreme heat events and enhancing a building's passive survivability. Passive survivability, defined as the ability of a building to maintain critical life-support conditions during utility outages, aligns closely with our discussion on resilience metrics in the built environment. This concept of passive survivability echoes the findings of other studies [60, 82], which also emphasize the importance of a building's ability to continue functioning during disruptions. The review by Houghton and Castillo-Salgado underscores the significance of integrating green building design strategies to improve resilience against extreme heat events, thereby contributing to both public health and environmental sustainability.

In addition, the research by Gautam et al. [89] presents a comprehensive approach to assessing the resilience of electric distribution systems integrated with distributed energy resources. Their study developed a probabilistic extreme event model, an impact assessment model, and an optimal restoration model for active distribution systems, using a non-sequential Monte Carlo Simulation framework. The resilience metrics proposed in this study, including the Expected Probability of Interruption (EPI), Expected Outage Duration (EOD), and Expected Energy Not Served (EENS), provided a nuanced understanding of the system's resilience against extreme events. These metrics, calculated for both individual load points and the overall system, offer a detailed analysis of the vulnerability and resilience of distribution systems. This approach is particularly relevant to the resilience in the built environment as it highlights the importance of considering the interdependencies of time-varying demand, renewable energy output, and energy storage characteristics in resilience assessment. Furthermore, the methodology and metrics used by Gautam et al. evaluated the resilience of energy systems in the face of climatic and technological disruptions, offering valuable insights for probabilistic value-based investment planning to enhance the system resilience [89].

These studies reinforce our key observations on resilience metrics in energy systems. They confirm the effectiveness of integrating renewable energy and innovative management strategies for enhancing resilience in the built environment. Collectively, they support our observations on the importance of holistic, adaptable, and sustainable approaches to resilience across various regions.

3.4. How to improve resilience

A large number of measures and strategies can be deployed and utilized to improve the energy resilience in the built environment against different disruptive events as mentioned in section 3.2. For example, resilience-oriented retrofits can improve the building performance under extreme weather events, energy storage systems increase survival time under the power shortage, renewable energy provides a feasible solution to cover the demand energy under an island mode, and advanced controls could fore-seen the extreme event and response properly to reduce the impact of disasters, etc. However, there is a lack of a systematic literature review for resilience enhancement strategies. This section summarizes a number of resilience enhancement strategies and their characteristics and contributions to different disruptive events, which are reviewed, classified and shown in Fig. 9. Generally, these strategies, found from the literature collected in this study, are classified into five groups: 1). Design; 2). Retrofit; 3). Predictive Control; 4). Micro-grid; and 5). Other approaches. Details of the proposed improved strategies are described below. Among them, design and retrofit are considered the most effective solutions against extreme weather events, such as heat waves, accounting for 14.3 % and 35.7 % of the total reviewed studies, respectively. Predictive control is another important measure for optimizing building system operations, accounting for 10.7 % of the studies. Micro-grid solutions are mostly used to help building systems survive power outages, accounting for 28.6 % of the reviewed studies. The remaining 10.7 % of studies utilize various resilience measures to improve building energy resilience.

3.4.1. Design

Many studies have been conducted in the past for analyzing building design at the early stages so that buildings can become more resilient against the extreme future climate. Some of the major designs related solutions that were discussed by past studies are summarized as follows.

1) Building Orientation

The orientation of the building, which is decided at the design stage, is often used for maximizing the natural daylighting and taking advantage of solar heat gain for heating [90].For example, the south-facing buildings in the northern hemisphere and north-facing buildings in southern hemisphere are common practices to maximize exposures to the sun in the cold climate. Similarly in the hot climate, the buildings can be oriented in such a way to minimize sun exposure and maximize shading effects. Building designs could help keep the building cool and reduce the mechanical ventilation demand.

2) Design Variants

When planning and constructing a building, architects and engineers thoroughly study and conduct tests on a variety of design options. By testing these design options, they can analyze numerous setups and assess their effectiveness in different situations. Some examples of these options are: the level of insulation, the window-to-wall ratio (WWR), glass type and window shading, building orientation, and the incorporation of passive design techniques [16]. In addition, Simulations can be conducted for replicating severe weather scenarios to see how the building would cope these hazardous conditions [91]. Simulations enable evaluations of different design alternatives and changes to lessen any possible damage and assure a quick recovery of building operations following such disruptive events.

3) Selection of building materials

Taking thermal mass properties as an example, architects can make careful choices of building materials. Materials with higher thermal mass can absorb and store the heat during the day and release it at night which helps to moderate the indoor temperature. The selection of building materials is critical during extreme weather events, and building envelope with high thermal mass can help to enhance the building resilience. Changing building materials during retrofit could be challenging due to significant capital cost as it involves extensive demolition and reconstruction.

4) Incorporating Passive Design Features

Passive design features such as natural ventilation or roof top garden (e.g., green roof) can enhance building's resilience during extreme events [92–96]. Natural ventilation coupled with a simple fan can help to modulate the air temperature inside the indoor space [73].

5) Elevated Mechanical Floor

An elevated mechanical floor is a raised floor that contains the main HVAC and electric systems. This type of design can improve the energy efficiency by reducing the distance the conditioned air travels in the ductwork [16]. Also, this design is effective in case of floods when the basement and first floor can become inaccessible.

6) Integration of Redundant Systems

Redundant systems imply the integration of secondary sources of power like generators or batteries. Case studies have proved that these measures were very effective during power outage. Hydronic Radiant Flooring systems use pipes underneath or embedded inside the building floors to distribute the heat evenly throughout the building [16]. This water-based system is more efficient than traditional forced-air heating systems and can operate for a longer time on secondary electric supply sources such as generators or battery storage linked to PV or thermal solar collector and hot water tank.

Several case studies have incorporated these design ideas. For example.

- Simulation study conducted in Canadian buildings tried to simulate future weather data using weather generator tools like CCWorld-WeatherGen and WeatherShiftTM [97]. To improve the resolution of the weather data, the Hadley Regional Model 3 (HRM3) was coupled with Hadley Climate Model 3 (HadCM3). The study concluded that buildings with higher insulation, lower window-to-wall ratio, higher zone ratio, and smaller outdoor air supply were less affected by climate change.

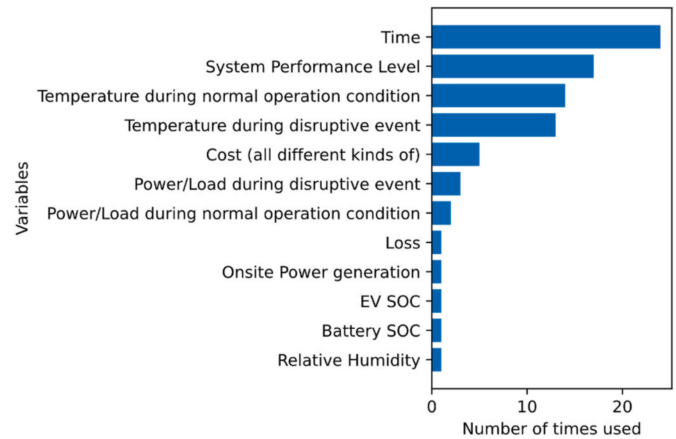

Fig. 8. Occurrence numbers for key variables used in resilience metrics.

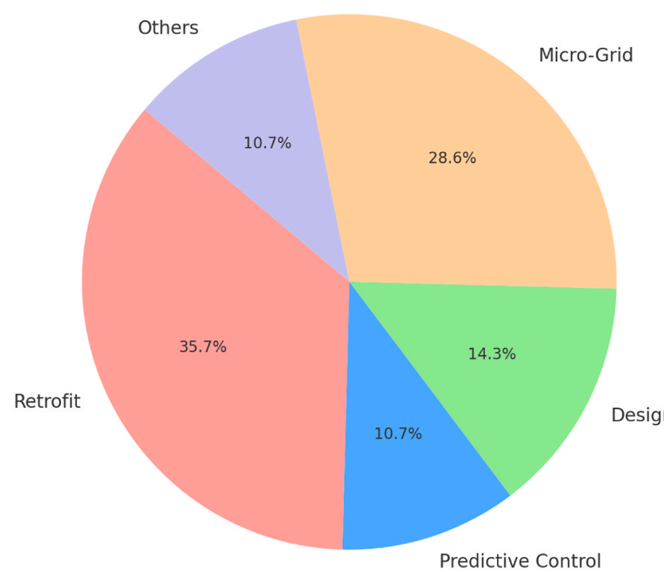

Fig. 9. Resilience enhancement solution categories with occurrence percentages.

- Simulation study in Macau, China, attempted to measure urban heat resilience (HR) using the Land Surface Temperature (LST) [98]. The study explained the impact of 3D and 3D urban built environment features on HR, using ArcGIS software for the LST estimation. Various tools from this software were used to estimate the solar radiation, brightness temperature, and roughness length index. The study also simulated the impact of Urban Heat Island (UHI) in the highly-densed Asian city of Macau. The study highlights the importance of vegetation in the city corridors to reduce the LST.
- Some studies have provided a framework and guidelines to help stakeholders like planners, engineers, and policymakers to make better-informed decisions for designing more resilient systems. For example, Shandiz et al. [17] developed a three-layered resilience framework by defining engineering, operational, and community resilience. Engineering resilience coped with physical assets and engineering-designed measures. Some examples mentioned that engineering-designed resilience layers are self-healing systems, resilient storage systems, and self-sufficient energy generation.
- Shandiz et al. [17] also described some measures for improving the district heating network system, power transmission network operation, and centralized power generation. Operational resilience is a

term for the set of technological and organizational measures, including demand side management, smart operation, and a ready supply of critical components. Finally, community resilience is defined as the cooperation and contributions of customers and other community stakeholders.

3.4.2. Retrofit

Building retrofit is a popular option to achieve higher resilience and energy efficiency [62]. The term 'retrofit' for any building not only refers to improving its envelope components like walls, roofs, windows, or doors. It also encompasses improving various building mechanical and energy components such as HVAC system upgrades, lighting improvements, renewable energy integration with solar panels and batteries, implementation of water efficiency measures, and many more. After reviewing various literature about the improvement of building resilience through retrofit, we noticed only limited types of retrofit measures were mentioned frequently. They are described briefly as follows.

1) Optimized Building Envelope Retrofitting

Effective retrofit interventions can significantly improve the energy resilience of buildings. This is a highly effective measure that can work against overheating during extreme weather events and also reducing annual space heating energy use [90]. The major interventions mentioned in the literature include increasing exterior wall insulation, solar control, ventilation enhancements, and adding exterior shading. For example, literature suggests the use of expanded polystyrene (EPS) insulation on exterior walls [37]. This type of insulation will help to reduce energy consumption, regulate indoor air temperature, and maintain a manageable thermal load.

2) Combining Mitigation and Adaptation Strategies

Some studies suggested that combining strategies for climate change mitigation and adaptation could lead to more energy resilient buildings. The technological interventions like insulation (external/internal and cavity wall insulation), solar control (solar reflective coatings, external shutters, blinds, curtains), ventilation, glazing upgrades and fixed shading devices coupled with behavioral interventions such as closing curtains during daytime and allowing night ventilation can enhance the resilience of building. It is essential to ensure that these strategies are designed with future climate scenarios in mind [90].

3) Passive Strategies

For regions prone to extreme heat events, passive cooling strategies can be beneficial. These may include increasing thermal insulation, reducing solar absorption, enhancing night ventilation, and installing green roofs or facades [99]. These measures can reduce the need for air conditioning and, consequently, lower energy consumption [62].

Katal et al. conducted a simulation study in Montreal, Canada, aiming to find the most effective measures that could have provided adequate resilience against the 'Storm of the Century' event of 1971 that took the lives of 30 people [37]. The study mentioned that adding an 80-m thick expanded polystyrene (EPS) layer to the outer surface of all the external walls of the building can double the insulations for old high-rise residential buildings. The zone temperature inside the building always stayed above the freezing temperature when this retrofit measure was applied, even with the 'Storm of the Century' event [100].

4) Active Energy Efficiency Measures (EEMs)

EEMs can improve thermal resilience and reduce the risk of heat exposure, particularly in critical buildings like nursing homes and hospitals. They can be instrumental in maintaining occupant safety and reducing energy usage, considering different climate zones and weather events [78].

Some studies have attempted to exemplify the points previously discussed.

- A study at a hospital building in the United Kingdom suggested the installation of a cheap fan to improve the hospital ward's thermal comfort instead of installing costly air conditioning systems [73].
- Another study on buildings in Sweden suggested increasing the thermal insulation and installation of more efficient lighting equipment for achieving resilience against extreme weather due to climate change in the future [101].

3.4.3. Predictive control

The use of Heating Ventilation and Air Conditioning systems has become an integral part of modern living in many parts of the world. In the United States, the prevalence of AC in residential buildings has grown substantially over the past few decades. According to data from the U.S. Census Bureau, the proportion of new construction residences equipped with AC increased from 49 % in 1973 to 93 % in 2016. According to the US Energy Information Agency, as of 2015, 87 % of homes were equipped with air conditioning (AC) [102]. Relying excessively on HVAC system can lead to occupants being exposed to dangerously overheating interior spaces [103]. Ji et al. [104] first time introduced resilient control concept into the building automation system, and pointed out that model-based building control can impact control system's resiliency. Advanced HVAC control can predict extreme event probability and facilitate the HVAC system to respond accordingly. Besides active controls through HVAC system, natural ventilation is also recognized as one of the resilience measures. It is relatively easy to implement natural ventilation in certain climate zones with low cost investments [75,105].

3.4.4. Micro-grid

Referred to the U.S. Department of Energy [106], a micro-grid is defined as "a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid." It is well known that "a micro-grid can connect and disconnect from the grid to enable it to operate in both grid-connected or island mode". Micro-grids are increasingly recognized as one of the most important measures to improve building resilience since "they are being used to improve reliability and resilience of electrical grids, to manage the addition of distributed clean energy resources like wind and solar photovoltaic (PV) generation to reduce fossil fuel emissions, and to provide electricity in areas not served by centralized electrical infrastructure" [107]. Consequently, in this study, we define a micro-grid as a set of generation units and energy storage systems that can operate in an off-grid mode to provide the necessary load centers' energy to satisfy the building energy system's demand under power system failure. This approach involves renewable energy and energy storage systems.

In addition to their general application, microgrids must be tailored to the specific needs of different building types. For instance, in healthcare facilities, microgrids were designed for redundancy and rapid response, ensuring that critical medical equipment remains operational during power outages. This approach was exemplified in the study by Reyes–Ascanio et al. [108], which highlights the installation of microgrids in healthcare settings to improve energy resilience, particularly focusing on the continuity of critical medical services.

In contrast, residential complexes might prioritize microgrid designs that optimize cost-effectiveness and adapt to variable energy usage patterns. The study by Chamana et al. [109] discussed the management of small-scale microgrids in residential settings, emphasizing the importance of directing available energy to critical loads and enhancing resilience in community microgrids. Commercial buildings, with their varied energy demands throughout the day, require microgrids that can dynamically adjust to changing load requirements. The evaluation of a microgrid in Northampton, Massachusetts, conducted by Balducci et al. [110], demonstrated how microgrids could provide economic and resilience benefits in commercial settings, including schools and hospitals, by linking various facilities and optimizing energy distribution.

3.4.4.1. Distributed energy resources. Renewable energy technologies, such as photovoltaic (PV), wind turbines, biomass, geothermal, hydropower, marine energy, etc., are developing rapidly worldwide. For example, the generation efficiency of wind turbines has been increasing and the price of solar panels has been decreasing annually which improves the scalability of building renewable energy generation technologies [107]. The integration of renewable energy and building energy systems demonstrated significant energy-saving potential while reducing the carbon footprint. Moreover, renewable energy also provides solutions for resilience enhancement. For example, a resilience assessment and quantification of the integrated energy systems addressed how the resilience of demand-side systems with multiple functions can be defined, characterized, and improved by PV generation systems [35]. Sepúlveda-Mora and Hegedus demonstrated that PV, wind, and local generators can improve the resilience index by up to 40 % in commercial buildings [111]. A summary of resilience improvement by using renewable energy was listed in Table 6. Notably, the "Performance evaluation" column in this table confirms that the community does not have a unified method and metric to quantify the resilience.

3.4.4.2. Energy storage system. Energy storage technology is commonly used as an energy buffer to store energy temporarily and release it for the future use [119]. It is mainly categorized as electric energy storage systems such as stationary batteries, batteries used in electric vehicles or thermal storage systems such as storages with phase change materials (PCM) [120], and thermal water tanks. Energy storage system plays a significant role in enhancing building resilience, because it can back up the demand energy before the disruptive event by charging the storage system and filling in the shortage of energy in case of a power failure by discharging.

3.4.4.3. Stationary battery. Battery storage systems are being increasingly adopted worldwide to address the intermittent and fluctuating nature of renewable energy resources and relieve the grid burden [82]. Lithium-ion batteries have become the preferred choice because of their fast response to load demand and high energy density with a long cycle lifetime [121]. The stationary battery storage system is usually considered as a flexible energy resource which can be charged in advance as a backup energy bank. Then the stored electricity can be used to support building energy system operation for several hours during a power outage event and increase the resilience survival time [35,49,50,63,112,122]. This can be formulated in Eq. (1) [50]:

$$E_{EU} = f(E_{PSS}, E_{BES}) \tag{1}$$

Where E_{EU} is the energy demanded by the electricity users (EU) in kWh; E_{PSS} is the energy supplied by the power supply system (PSS) configuration in kWh; and the E_{BES} is the energy available or supplied by the battery energy storage in kWh [50].

3.4.4.4. Electric vehicles. Electric vehicles as another type of energy storage device are gaining popularity rapidly over the last decade. Similar to stationary battery systems, electric vehicles have the capacity to improve building resilience by changing charging and discharging schedules during a disruptive event, which can be modeled by Eqs. (2)–(4) [51]:

$$P_j^{EV} = \underline{P}_j^{EV} \times 1_j(t) \leq P_{j,t}^{EV} \leq \overline{P}_j^{EV} \times 1_j(t) \tag{2}$$

$$SOC_{j,t} = SOC_{j,t-1} + n_j \frac{P_{j,t}^{EV}}{E_j} \Delta t \tag{3}$$

$$\underline{SOC_j} \leq SOC_{j,t} \leq \overline{SOC_j} \tag{4}$$

Where n_j is the efficiency of power exchange, E_j is the energy capacity of EV battery, 1_j is the indicator function, which equal to 1 when EV is available for charging. $\underline{SOC_j}$ and $\overline{SOC_j}$ denotes as the lower bound and upper bound of charging state. Unlike a stationary batteries, electric vehicles are adaptive electric energy storage devices. Their storage capacity and charging-discharging behavior are constrained by travel parameters such as travel distance, daily arrival-and departure time, and the initial state of charge, among others [123]. For example, Dong et al. proposed a multi-phase resiliency-oriented rescheduling strategy for multiple EVs, which aimed at reducing the essential load curtailment while satisfying EV energy requirements when leaving home [51]. 30 % of the essential load curtailment was reduced and it can be improved to 61.5 % by reinforcing the interconnection line. Mauricette et al. pointed out that EV2Grid control can greatly reduce the number of essential loads during a power outage [124].

3.4.5. Others

Several other resilience measures, explored in the literature, are listed as follows.

- *Policy and standard establishment.* This covers establishing a clear resilience terminology for the built environment to facilitate effective communication of new concepts; creating guidance for community resilience planning; identifying technical gaps and research needs, developing risk-based performance goals for resilient communities; designing tools and metrics to support quantitative technical assessment, policy development, and decision-making processes; and formulating guidelines on risk-based performance goals and criteria to be included in standards for voluntary reference [34,125].
- *Urban planning measures.* Voskamp et al. studied 'Blue-green measures' which is a collective term for combined green and blue infrastructure and link enhanced storage [40]. It can be used for cooling via evapotranspiration, water storage for heavy rainfall events, discharge peak attenuation, seasonal water storage, and groundwater recharge.
- Structural measures: This approach involves strengthening and retrofitting existing buildings and infrastructure to make them more resistant to damage from natural disasters and other disruptive events. Exemplary structural measures include reinforcing buildings to withstand high winds, installing flood barriers, and elevating critical equipment [126].
- *Training measures*: Modern building systems require the building operators with more diversified expertise, skills and background. For example, supplier crew is responsible for thorough preparation ahead of the outage; the reserve crew is available to respond promptly and aid in faster system recovery; and the system manager is tasked with operating the system correctly. Meanwhile, residential end users need to learn how to use generators, prepare critical supplies of medicines, food and other necessities beforehand [29], and for power companies, they were advised to be prepared to survive the immediate aftermath of any critical emergency.

In a short summary, this section provides the commonly used resilience improvement strategies in terms of design, retrofit, predictive control, micro-grid and other solutions. Among them, design strategy focuses on the early stage of buildings' life cycle, which can improve the building resilience more effectively and efficiently with lower capital investments. Retrofit aims at improving target building environment especially under extreme weather condition. Predictive control strategy can increase the building resilience by optimized control algorithm which probably is the most cost-effective and viable approach. Microgrid demonstrates great resilience potentials during an island mode

Table 6
A summary of resilience improvement by renewable energy.

Resilience Source	Software	Disruptive event duration time	Outage frequency	Disruptive event	Performance evaluations	Reference
PV and battery	Simulated integrated energy system	Summer day & night Winter day & night	N/A	Power outage	Proposed PV-Battery system can improve the resilience index of the system by 18.1 % for both "Summer Day" and "Winter Day".	[35]
PV, wind, battery storage, and generator	Homer grid simulation	3 days	N/A	natural disasters and extreme weather	Proposed microgrid emits 79 % less CO_2 while brings life-cycle savings of 37.02 million USD.	[63]
PV, battery and diesel generators	REopt simulation	8, 16 and 24 h	N/A	Power outage	Save $440,191 over the 20-year life cycle, increasing resilience time to 34 h.	[112]
Wind, PV, battery banks, generator	Stochastic optimization	Long term evaluation	Scenario based frequency	Extreme weather	Renewable energy uncertainties can cause up to 34 % of performance gap and 16 % power supply reliability drop due to extreme weather events.	[65]
PV, battery	Matlab simulation	168 h	N/A	Extreme weather	Proposed microgrid can improve building resilience by 46.9 %.	[49]
Electric grid (EG), natural gas power generator (NGPG), battery energy storage (BES), and PV	Homer simulation	Three major power outage events occurred in New York with 1.2h, 3.1h, and 311.9hduration	N/A	Power outage	BES can't work for long power outage scenarios. NGPG improved resilience but increased cost. EG + PV + BES enhance overall resilience	[50]
PV + BES + wind + Diesel Generator	HOMER	92h–236 h/year	61-94/year	Power outage	Grid/diesel/PV/battery systems are feasible for all three climate regions with the cost of energy at 0.044, 0.049, and 0.048 $/kWh, the CO2 emissions decreased by 45 %, 44 %, and 42 %	[113]
PV + BES + DG	HOMER	08:00–11:00 on every day in February; 12:00–16:00 from Monday to Friday in May; 04:00–06:00 on Saturdays and Sundays in September		Blackouts	Generators provide economic benefits for short-term power outages, while PV batteries offer greater savings for long-term power outages.	[114]
PV + BES	HOMER	2 and 3 a.m.; 8 and 9 a.m.; 3 and 4 p.m.	Every day	Power outages	Proposed grid-tied PV system can contribute 53 % of the energy demand while reducing 3558 kg GHG emissions.	[115]
PV + BES	HOMER	2 h average	1800 failures per year	Power outages	Battery system achieves high renewable fraction (64.9 %) and low CO_2 emissions (4533 kg/year). While a diesel generator reduces net present cost by 11.6 % but increases CO_2 emissions by 32.7 %.	[116]
PV + BES + DG	HOMER	8:00 a.m. to 5:00 p.m.	daily	Power interruption	Minimum size of BESS was optimized	[117]
PV + BES + DG	HOMER	1 h	260 per year	Power outages	1) A 45 % reduction of the maximum fuel consumption. 2) A 19 % reduction in levelized cost of electricity, and 3) A 26 % internal rate of return.	[118]

under power outage. The other solutions stand from policy maker or urban planner point of view, which also provides possible resilience enhancement. For different stakeholders who are affected by various disruptive events, it is crucial to identify and implement tailored resilience improvement solutions. Section 4 provides a comprehensive guide, offering detailed instructions for stakeholders to select the most suitable resilience measures based on their specific needs and circumstances.

4. A framework to evaluate and improve building resilience

According to the reviewed building resilience enhancement strategies in the literature, we proposed five steps to choosing appropriate resilience improvement strategy as follows.

1) Step 1: Determine who is the stakeholder, six types of potential stakeholders were categorized as power company, policy maker, building manager, building owner, occupant, and architect designer. Different stakeholders might have different interest and focus.
2) Step 2: Determine what is the resilience scope/level. The scope of resilience was divided into six groups, namely urban scale, community scale, grid level, micro-grid level, building level, and system level.
3) Step 3: Determine what is the disruptive event. Based on the climate condition and local grid stability, the dominated disruptive events were different case by case. Four disruptive events were categorized, in consistent with section 3.2, we combined groups of "Heat wave", "Hurricane/Typhoon", "Winter storm" and "General extreme weather events" into one group of "Extreme weather". The "Others" and "Not mentioned" were considered as "Specific failure". And "Component failure" was categorized as "Power outage", and a detailed description can be found in section 3.2.
4) Step 4: Evaluate the current resilience status using KPIs which are occupancy-based metrics, grid related metrics, infrastructure metrics, economic metrics and hybrid metrics. A detailed introduction of these KPIs can be found in section 3.3. Before stepping into resilience enhancement, a basic assessment is needed to evaluate the current situation. For the building suffered by disruptive events, the subsequent step is to determine the resilience scope or level.
5) Step 5: Based on these four steps and available resilience enhancement measures, we listed five resilience improvement solutions which were design, retrofit, micro-grid measure, predictive control and other solutions. Section 3.4 can be used as a reference to look up for improvement solutions.

Fig. 10 illustrates this proposed framework through five steps indicated by five columns. This figure further shows the interaction between stakeholders, KPIs, resilience scope, disruptive event, and resilience improvement solutions among the literatures we reviewed. The color scale differentiates among stakeholders. The thickness of the line connecting each column represents the number of reviewed cases from the previous category to the subsequent category. Each column has different categories according to the definitions listed in previous sections.

Let's assume we are considering a scenario from one case study in the literature. Flores-Larsen and Filippín investigated the indoor environment of low-income families during extremely hot weather conditions on occupants' health and discussed the performance of passive cooling measures to improve heat resilience [62]. In Fig. 10, the green line represents the path that this case study follows, illustrating the application of the proposed framework.

1) Stakeholder Identification: The stakeholder in this case is the occupant. Given the direct relationship between the living environment and their well-being, the occupants' primarily concern is that their building can continue to be functionable under extreme weather conditions.
2) Determine Resilience Scope/Level: The resilience is scoped at the building level.
3) Disruptive Event Identification: The disruptive event in this case is the extreme heat event, which is categorized under general extreme weather events.
4) Resilience KPI Evaluation: Concerning the extreme hot condition, the heat index, an occupants' metric, is selected to evaluate the building thermal resilience. Evaluating the building's thermal resilience using the heat index highlights the direct impact of resilience strategies on occupant health and comfort. This quantitative approach, as outlined in Section 3.3, allows for a precise assessment of the building's capability to maintain habitable conditions during extreme heat events. The heat index, by accounting for both temperature and humidity, provides a comprehensive measure of the indoor environment, reflecting the practical effectiveness of the implemented strategies.
5) Resilience Improvement Solutions: The suite of retrofit measures identified in this case study, including ventilated opaque facades, improved roof design, and added thermal insulation, directly correlate to the Design and Retrofit strategies discussed in Section 3.4. These practical passive strategies demonstrate how specific design changes can significantly enhance a building's resilience to extreme heat. The effectiveness of these measures is underscored by their impact on the heat index, showing a tangible improvement in the thermal comfort inside the building. This practical application exemplifies how tailored retrofitting can effectively mitigate the adverse effects of extreme weather conditions, thereby enhancing the overall resilience of the built environment.

This case study serves as a concrete example of how the theoretical frameworks and strategies discussed in our study are applied in real situations. It not only validates the proposed resilience metrics and strategies but also provides insightful guidance for their implementation in similar contexts.

To evaluate resilience metrics, we propose the workflow, as shown in Fig. 11, in choosing appropriate resilience metrics. Taking the same study from Flores-Larsen and Filippín [62] as an example again, following steps will be applied.

1) Stakeholder Identification: As in the previous scenario, the occupant is the stakeholder.
2) Scope/Level Determination: The focus remains on the building level.
3) Goal of Energy Resilience: The goal could be to ensure occupant comfort and safety during disruptive events.
4) Check Subset KPIs: The occupant should check if existing KPIs, such as heating index, indoor overheating degrees, and discomfort index during disruptive events provide enough information about their building's resilience.
5) Development of New KPIs: If existing KPIs are not sufficient, the occupant might need to develop new KPIs. For instance, they might need to consider how quickly their building can be operational after an extreme weather event, or how comfortable occupants are during such events, if such metrics have not been previously considered.

Please keep in mind that each scenario is unique and different, so the most important action is to understand the specific conditions, interests, and capabilities of the stakeholder in question, and apply the framework accordingly.

In light of the critical importance of retrofit interventions for enhancing energy resilience, we recognize that strategies such as increasing exterior wall insulation, solar control, ventilation enhancements, adding exterior shading, and elevating mechanical floors, especially in flood-prone areas, are integral. These measures, along with the integration of redundant systems like generators or batteries, play a pivotal role in maintaining operational continuity during power outages and other disruptive events. Furthermore, the adoption of hydronic radiant flooring systems, being more efficient than traditional forced-air heating systems, represents a significant advancement in retrofit technologies [127].

Moreover, from a regional planning perspective, these retrofit interventions can be crucial in fostering the development of cost-effective energy optimization methods, particularly in ecologically disturbed regions. This concept is supported by the study presented in Ref. [128], which focused on arsenic pollution in groundwater and its remediation in India. While the context of this study is different, it offers valuable insights into the utilization of locally available resources for addressing environmental challenges. The research emphasizes the commercial fixation of waste into building materials as a method for encapsulating toxicity and promoting sustainable mitigation strategies.

Additionally, a recent study by Badiei and Campos do Prado [129] provided a contemporary perspective on the feasibility of solar

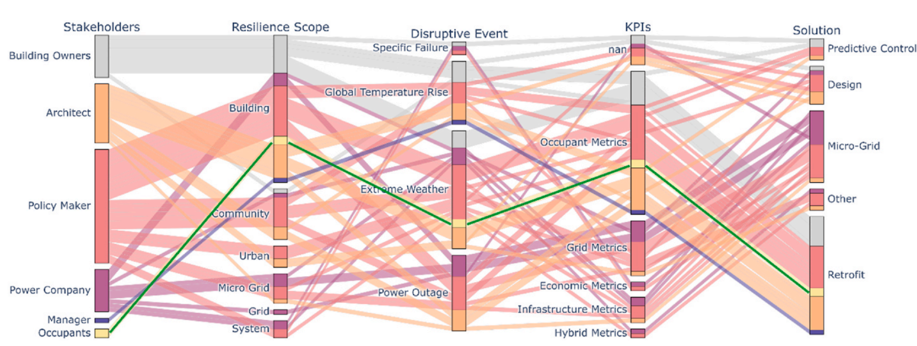

Fig. 10. A general framework to evaluate and improve building resilience.
(Note: the green line represents the evaluation and improvement path that one case study from Ref. [62] could follow if using the proposed framework).

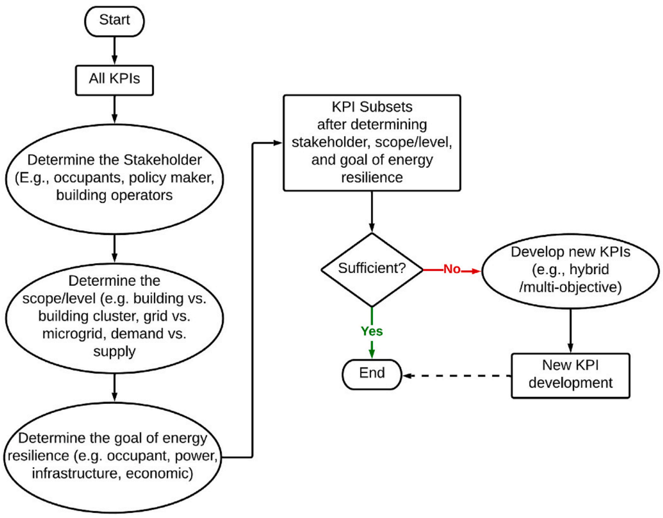

Fig. 11. Energy resilience KPIs selection workflow process.

photovoltaic (PV) and battery energy storage (BES) systems in commercial buildings, considering both financial and resilience aspects. This study examined the impact of electricity rates on the viability of these systems through optimizing their size for different geographic locations, load profiles, and outage durations. The findings highlighted the importance of integrating solar PV and BES systems into building retrofits, not only for financial benefits but also for enhancing resilience against power outages and other disruptions. This approach aligned with our proposal of using locally sourced materials and renewable energy sources for retrofit interventions, emphasizing the potential of such strategies in developing region-specific, cost-effective, and sustainable energy resilience solutions.

Furthermore, the research conducted by Trimmel et al. [130] offers critical insights into the thermal conditions during heat waves in a mid-European metropolis, considering the effects of climate change, urban development scenarios, and resilience measures for the mid-21st century. This study underscored the significance of urban planning and building design in mitigating the impacts of heat waves, emphasizing the need for near zero-energy standards and increased albedo of building materials. The findings suggested that local-scale changes, such as insulation of buildings and measures to reduce mean radiant temperature within urban canyons, were essential to complement city-scale strategies. This study emphasized on the retrofit interventions and demonstrated the importance of considering both micro and macro-level urban planning strategies to enhance resilience against extreme climatic conditions.

In addition, the study by Menna et al. provides a comprehensive analysis of methods for the combined assessment of seismic resilience and energy efficiency in European building retrofitting [131]. This research illustrated the significance of integrating seismic resilience and energy efficiency considerations in retrofitting projects, particularly in regions vulnerable to earthquakes, floods, and wildfires. It advocated for site-specific assessment tools and a holistic approach that considers all aspects of building performance and potential damage. This perspective aligns with an emphasis on retrofit interventions and underlines the importance of multi-objective evaluations for developing sustainable and resilient retrofit strategies tailored to specific regional contexts and challenges.

Besides, the study conducted in Zanjan [132] presented a comprehensive approach to the renovation of residential buildings in historic districts, with a focus on sustainable and resilient developments. Utilizing the Delphi method and analytic hierarchy process, this research evaluated the importance of various sustainability and resilience factors. It underscored the significance of adaptable building thermal insulation, green areas, and connectivity as essential components for resilient urban design, where retrofit interventions and underlines the importance of considering sustainability and resilience in urban revitalization, especially in historic areas, are the focus. The findings contribute valuable insights into how retrofit interventions can be effectively implemented in diverse urban contexts to achieve both sustainability and resilience.

Jankovic's work [133] delved into the resilience design at various levels, encompassing the building, the site, and the region. It brought to the force the importance of multi-objective optimization in retrofitting buildings, particularly in the context of changing climate conditions. The study also emphasized the significance of green areas and adaptable connectivity in enhancing resilience at both site and regional levels. This comprehensive approach, which considered immediate and future climatic scenarios, employed sustainable and adaptable retrofit strategies. The insights provided by Jankovic are instrumental in understanding the practical implications and strategies necessary for designing resilience in the built environment, thereby reinforcing the necessity of a multi-layered approach in resilience planning.

In summary, these studies demonstrate the critical importance of retrofit interventions in enhancing energy resilience and sustainability in the built environment. These studies collectively emphasize the need for multi-objective optimization, incorporating aspects such as exterior wall insulation, solar control, green areas, and redundant energy systems like solar PV and BES. Particularly noteworthy is the focus on using locally sourced materials and renewable energy sources in retrofit interventions, which should be cornerstones for developing region-specific, cost-effective strategies. This approach is essential for addressing the unique challenges faced in ecologically disturbed regions, supporting the idea that such retrofit strategies, when thoughtfully applied, can significantly contribute to sustainable urban development and energy optimization across diverse geographic spectrums. This perspective substantively elaborates on the aspects needed for effective regional planning.

5. Conclusions

In conclusion, enhancing energy resilience in the built environment is of paramount importance for developing effective strategies and policies to mitigate the impacts of disruptions. However, the absence of a universal definition of energy resilience in this context presents challenges in comparing and integrating research findings. Resilience in the built environment encompasses key concepts such as vulnerability, resistance, robustness, and recoverability, and addressing these aspects is vital for a comprehensive understanding. The resilience trapezoid concept offers a valuable framework for illustrating the stages a building or system undergoes during a disruptive event and serves as a foundation for defining and calculating resilience-related metrics. This review proposes the follow definition:

Energy resilience in the built environment refers to the inherent and adaptive capacity of buildings, infrastructure, and urban energy systems to anticipate, absorb, recover from, and adaptively respond to disruptions in energy supply and demand, while ensuring sustained functionality, efficiency, and equitability both in the short and long term.

The proposed definition is generic, as energy resilience in the built environment is a complex and multifaceted issue. This definition aims to reflect the multi-dimensional approach, holistic understanding, and consideration of multiple levels of scale, as suggested by this literature review. In practice, the proposed definition can be combined with other more specific definitions, metrics, models, and strategies for different contexts and purposes, e.g., to evaluate the vulnerability of the current state of buildings and to identify enhancement measures for a certain disruptive event.

Disruptions affecting energy resilience in the built environment can be systematically classified into categories, including meteorological, climatological, technology malfunction, and not mentioned. Heat wave and component failure are the two most frequently analyzed and discussed disruptions in the existing literature.

A variety of quantitative metrics are employed to assess resilience in the built environment, which can be grouped into five categories: Occupants' Metrics, Grid Metrics, Infrastructure Metrics, Economic Metrics, and Hybrid Metrics. Occupants' Metrics and Infrastructure Metrics are the most popular, prioritizing human well-being and infrastructure robustness. While less prevalent, Grid Metrics and Economic Metrics provide insights into the effects of energy disruptions on the power grid and the broader economy. Time, system performance level, and temperature during normal and disruptive events are critical variables in resilience metric calculations, as they enable the evaluation of system robustness, adaptability, and recovery from disturbances.

This study presents a comprehensive review of resilience enhancement strategies, categorized into five main groups: 1) Design; 2) Retrofit; 3) Predictive control; 4) Micro-grid; and 5) Other approaches. These strategies offer numerous benefits, such as enhancing building environments during extreme weather events, prolonging survival time during power shortages, utilizing renewable energy for demand, and employing advanced controls to mitigate disaster impacts. This study proposes a generic and adaptable framework to bolster energy resilience in the built environment. This multifaceted approach initiates with the identification of stakeholders, spanning from power companies to architect designers, and their distinct interests. The scale of resilience is then determined, ranging from the system level to an urban scale. The disruptive event, whether it's a power outage or extreme weather, is then defined. The subsequent step involves evaluating of the building's existing resilience through key performance indicators, such as occupancy, power, and economic metrics, enabling stakeholders to explore appropriate resilience enhancement measures. These could include solutions like retrofitting, micro-grid measures, design alterations, or predictive controls. Overall, this framework accommodates a range of scenarios and stakeholders, providing a comprehensive workflow to augment resilience in the built environment against potential challenges.

It is also worth noting that the minimum performance level for each metric varies on a case-by-case basis. Most reviewed studies did not specify the minimum accepted performance from an energy resilience perspective. Therefore, in future work, we plan to study and investigate each metric's minimum performance level under specific circumstances. Besides, we plan to delve deeper into the connection between energy resilience and energy flexibility in buildings. Buildings and building clusters that are energy flexible can improve the resilience of energy networks by reducing the load on the infrastructure. This also makes buildings more resilient to fluctuations in energy supply. When assessing resilience, it's often related to a building's ability to change its electricity use during a grid service or in the face of severe weather. Energy flexibility and resilience tend to have a close, sometimes inverse, relationship, as measures to improve resilience, such as reserving battery power for emergencies, can reduce the building's flexibility. The future work will focus on the design and optimization of adaptive building and community energy systems and controls to uncover the relationship and balance between system flexibility and resilience.

CRediT authorship contribution statement

Mingjun Wei: Methodology, Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Zixin Jiang:** Data curation, Formal analysis, Investigation, Visualization, Writing – review & editing. **Pratik Pandey:** Data curation, Formal analysis, Investigation, Visualization, Writing – review & editing. **Mingzhe Liu:** Data curation, Formal analysis, Investigation, Visualization, Writing – review & editing. **Rongling Li:** Conceptualization, Supervision, Data curation, Formal analysis, Investigation, Writing – review & editing. **Zheng O'Neill:** Supervision, Methodology, Data curation, Formal analysis, Investigation, Writing – review & editing. **Bing Dong:** Data curation, Formal analysis, Investigation, Writing – review & editing. **Mohamed Hamdy:** Data curation, Formal analysis, Investigation, Writing – review & editing.

Declaration of competing interest

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

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Data availability

Data will be made available on request.

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