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Review

Impact of Power Interruption on Buildings and Neighborhoods and Potential Technical and Design Adaptation Methods

Caroline Hachem-Vermette * and Somil Yadav

Department of Building, Civil & Environmental Engineering, Gina Cody School of Engineering and Computer Science, Concordia University, Montreal, QC H3G 1M8, Canada; somil.yadav@concordia.ca
* Correspondence: caroline.hachemvermette@concordia.ca

Abstract: This paper presents a state-of-the-art review of the impact of energy interruptions on people, buildings, and neighborhoods and discusses some technological and design strategies to mitigate some of these impacts. An exhaustive literature review was carried out employing keyword searches in the ScienceDirect and Scopus databases. The literature focuses mainly on 37 keywords, which occurred in more than two sources. Based on this literature survey, the paper highlights that, depending on their duration, power outages can have a severe impact on people, buildings, and neighborhoods. The lives of vulnerable individuals dependent on electrical medical devices can be threatened even in short-term power interruption scenarios. Longer-term power outages affect multiple aspects of daily life, such as communication, thermal comfort, life quality, transportation, health, and security, in addition to potential damage to buildings and their contents. The paper identifies and discusses various methods that can be implemented to reduce vulnerability and improve adaptation to climate-related power interruptions. These methods range from simple, low-tech solutions that enable users to temporarily cope with hours of interruption to more sophisticated methods requiring advanced planning. These adaptation and coping methods are classified according to various criteria, including their ease of implementation, accessibility, potential cost, ease of use by occupants, and their potential to address various needs. The paper finally discusses the impact of building and neighborhood design on improving adaptation to energy interruptions. High-performance building design can extend the time that a building can passively operate without reliance on mechanical systems for heating and for cooling. Building shape and geometry, as well as the spatial design of the neighborhood, can maximize solar access and therefore facilitate the implementation of PV and solar technologies. In addition, the design of mixed-use neighborhoods with access to various facilities and basic amenities assists in prolonging the self-reliance of the community as a whole. This work aligns with the vision of the Sustainable Development Goals: by identifying methods and technologies to reduce the impact of power interruptions and improve the energy resilience of urban areas around the globe, this work can contribute to the direct and indirect fulfillment of several Sustainable Development Goals (e.g., SDGs 7, 11, 13, and others). Although the work is performed in a North American context and specifically refers to the Canadian climate, the methodology can be implemented in other climatic and regional conditions.

Keywords: energy resilience; Sustainable Development Goals; climate crisis; energy interruption; renewable energy sources; building and neighborhood design

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1. Introduction

Modern societies are significantly dependent on electric power to provide essential needs, including food and adequate living environment, as well as to power various activities including communication and transport [1]. The interruption of the electricity supply can cause significant damage to daily life activities and services, including household practices and basic needs, transportation systems, banking and financial systems, health services, and communication [2,3]. While maintaining a reliable and continuous electric

supply might be challenging under regular conditions [4,5], anomalous conditions such as an extreme natural event can significantly increase the impact of this challenge [6].

The occurrence of extreme weather-related disasters, such as hurricanes, wildfires, and floods, has significantly increased during the last two decades. For example, the average number of disasters in the United States doubled in the period between 2014 and 2018, as compared to the average number of climate disasters that occurred between 1980 and 2018 [7,8].

A review of worldwide extreme weather events highlights that many of these events have a major effect on power grids, causing extensive power outages that in some cases may last for days, weeks, or even months (e.g., during Hurricane Sandy [9–11] and the ice storm in Canada [12,13], etc.), leading to prolonged electrical interruptions and major economic losses. Experiences with the energy infrastructure during the last two decades have demonstrated that the electricity network in European and North American countries is not as dependable and robust as was generally assumed and that it can be significantly affected by various weather events. Bushal et al. [7] provide a summary of major blackouts, technical problems, and cyber-attacks caused by weather events based on data collected from research papers and reports. To enhance communities' continuous functioning and sometimes survival during power interruption, there is a need to comprehensively understand the impact of power outages on various aspects of human life and the environment, to identify factors affecting the magnitude of these impacts, and to recognize existing and potential technologies that can mitigate these impacts, as well as their feasibility and limitations.

The existing literature on the impacts of power interruption is both generally scattered and does not clearly highlight the relation between the magnitude of these impacts and various factors related to humans and their environment. Although the role of technologies in enhancing energy resilience is increasingly investigated, a focused review of these technologies, their capabilities, and their limitations, with respect to feasibility criteria, has not yet been presented at the building and neighborhood scale.

The existing literature focuses mostly on specific issues during power outages and discusses specific solutions, such as thermal resilience, resilient cooling, and distributed energy generation, e.g., [14–17]. Although such issues and solutions are undeniably significant in improving the resilience of the built environment, it is vital to understand that the severity of the impact of power outages on households is affected by various factors. These factors include access to alternative methods of energy generation, the energy efficiency of buildings, other basic design features including building type, and the diversity of fuel types serving various functions (e.g., all-electric vs. hybrid for heating, cooling, etc.). In addition, the type and size of the neighborhood can play a significant role in the severity and duration of the disruption [18].

The severity of energy interruption goes beyond the energy systems themselves to affect other basic systems in the built environment, such as water, health, and economic systems. This is especially important due to the interaction of these systems leading to cascading effects during an unanticipated disruption or disturbance [19,20]. For instance, water systems rely on energy to bring water to buildings, and any prolonged energy disturbance can impact water supply. Various health problems can also result from large and prolonged energy interruptions [21,22].

Reducing vulnerabilities is a key concern of the Sustainable Development Goals (SDGs). For instance, the implementation of renewable energy technologies to support energy supply from local grids can lead to more sustainable and resilient cities (SDG 11), help mitigate the impact of climate change (SDG 13), and constitute a key aspect of affordable and clean energy access (SDG 7) [23]. Despite the importance of improving the energy resilience of communities, there are enormous gaps both in research and implementation [23]. For example, developing solutions that recognize the interconnection of critical infrastructure structures and their vulnerability to disruptions can induce events with major cascading effects on the social, economic, and environmental levels [23,24]. To meet some of the SDGs, it is increasingly important to multiply efforts toward the implementation

of green technologies that can reduce the energy consumption of the built environment, reduce waste, and promote renewable energy generation and advanced energy management systems (e.g., community energy systems) while developing sustainable policies that support these efforts [23,25–27].

The paper aims to achieve the following: (1) present a state-of-the-art review of the impact of power interruptions on buildings and neighborhoods, (2) discuss the available technologies for reducing the impact of these interruptions, and (3) highlight design strategies for improved energy resilience. The paper provides an information-based tool to implement evidence-based energy-conscious design scenarios, thus assisting in designing resilient and sustainable urban developments. The merit of this focused review work lies in providing key insights that can drive future research, inform resilience policies, and assist in establishing practical procedures to reduce vulnerabilities. Moreover, identifying methods and technologies to reduce the vulnerability of urban areas to energy interruption contributes significantly to the Sustainable Development Goals, both directly and indirectly. The contribution of improved energy resilience in communities to the SDGs is discussed in the manuscript.

2. Methodology

Three main topics form the focus of this paper: (1) identifying the impacts of power outages on households' daily practices; (2) discussing various technologies for mitigating some of these impacts and reducing vulnerability during outages; (3) analyzing the role of building and neighborhood design in improving energy resilience. A neighborhood is considered in this work as a geographic area encompassing a number of buildings and their surroundings, featuring various land uses and associated infrastructure. A building is a single physical construction dedicated to a single or mixed use.

An extensive literature review was carried out in two major fields: the impacts of power interruptions on human survivability and their built environment, and potential technologies employed to mitigate, in different capacities, these impacts. Relevant literature (journal articles and reports) was identified through keyword searches in the ScienceDirect and Scopus databases, and a network visualization illustrating the relationship between keywords in the current literature review is presented in Figure 1. The literature focuses mainly on 37 keywords, occurring in more than two sources. A few keywords, such as critical infrastructure and solar irradiation, have been neglected due to weak link strength. This enhances the credibility of the review and is implemented in a number of current studies, e.g., [28,29]. The selected keywords were imported into VOS viewer 1.6.19 software to generate the visual maps. The size of a keyword's label and circle corresponds to its frequency in the cited literature, with more prominent items having larger labels and circles. These keywords are further clubbed together and presented by different colored clusters. The lines connecting clusters represent the connections between them. From the figure, it is evident that power outages are connected with natural disasters and climate change. Additionally, resilience in such events is associated with renewable energy sources, including solar energy and fuel cells, which are further linked to storage technologies. Smart grids and microgrids establish connections between storage technologies and demand-side management. All these facets are extensively discussed in the literature review. Figure 1 also illustrates the evolving research trends in these domains over time. The color bar in the right corner indicates the year of the cited research articles. It is evident from Figure 1 that the current emphasis is on studying power outage resilience.

In processing the various literature sources on outage impacts, topics need to be narrowed down to various specific criteria, such as the length of the power outage, health and safety impacts, communication, and other specific needs, to obtain meaningful results. The main observations are then grouped into tables to provide a holistic picture of the impact of power interruptions on various human needs.

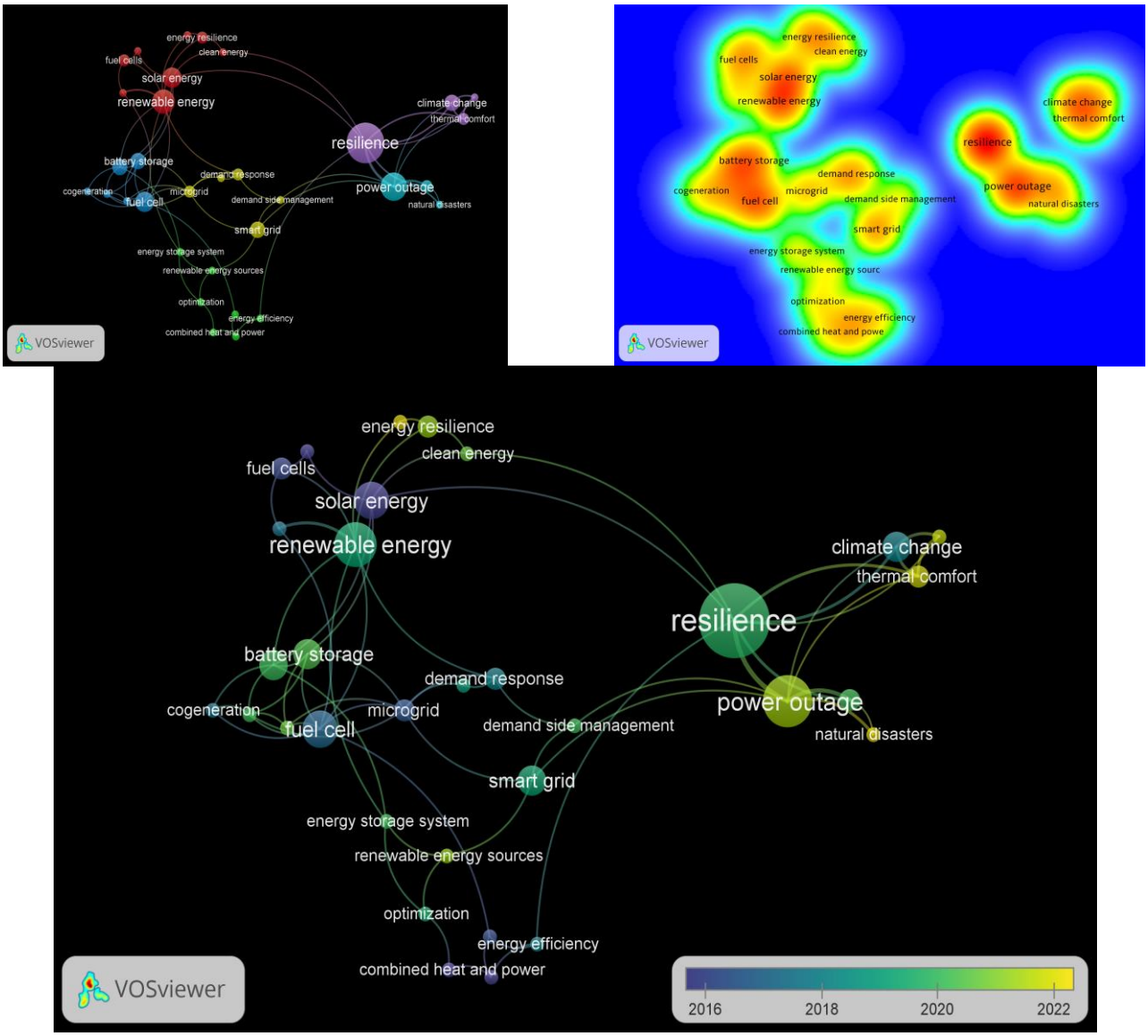


Figure 1. Visual representation of keywords in the current literature review and evolving research trends over time for the keywords in the current literature review.

The literature review on technologies employed to mitigate the impacts of power interruptions yields knowledge about technologies employed in specific circumstances (such as PV with batteries, combined heat and power generation, etc.) and highlights the role of distributed energy in general. A list of potential distributed energy technologies at the building and neighborhood level is then developed, and each of these is individually reviewed employing pertinent literature to identify their potential and their limitations.

The third part of this paper is based on the extensive research of the author related to the impact of building and neighborhood design parameters to allow energy efficiency and to optimize the implementation of various renewable and alternative energy resources, thus improving the overall resilience of a community. Figure 2 presents an illustration of the approach applied in this paper.

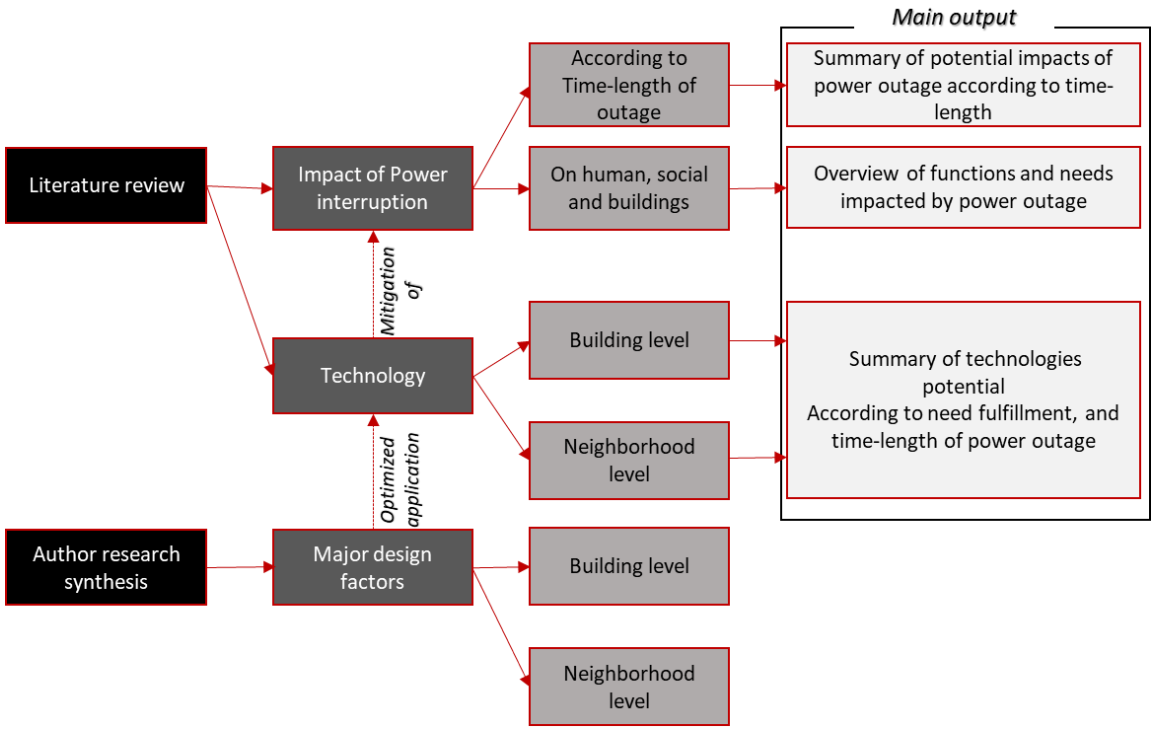


Figure 2. Illustration of the general approach employed in the paper.

3. Impacts of Power Outage

Power outages can have a range of direct and indirect impacts on humans and their environment [30,31]. The literature on technical issues related to power outages is increasing; however, studies that explore the psychological and emotional impacts of power outages are scarce to nonexistent [31].

This section assesses the potential impacts of power outage crises, which often result from an extreme climate crisis, on livelihood and survivability in residential buildings. The impacts are determined for varying outage durations, considered short-term (hours), medium-term (days), and long-term (weeks). The impacts are mostly classified in terms of communication, comfort (heating/cooling, warm water, electric lighting), food and water (e.g., nutrition, cooking, water supply), safety, security, damage to dwelling content, damage to dwelling itself, health concerns, and threat to life.

The impacts are discussed according to different types of residential buildings as well as the demographic of occupants (e.g., elderly and vulnerable individuals, families with vulnerable individuals, and young couples/single individuals). A literature survey was conducted to identify the common and specific impacts of power outages on residential buildings and their inhabitants.

The impacts can change dramatically according to the length of the outage. Some of the expected impacts are summarized below, according to the outage duration, and in Table 1.

- Short-term outage (<24 h):

Although a short-duration outage of less than 24 h has a limited impact on people and buildings, some serious damage can still occur. For instance, for vulnerable people who depend on electrical medical devices for survival (heart, breathing, etc.), even a short-term power outage may lead to life-threatening situations [32,33].

Other critical functions that can be affected by short-term outages include a potential interruption in communication, such as reliance on cellphones (with limited battery duration) [34,35]. In addition, thermal comfort can be compromised in low-performance buildings during extreme cold or heat waves [36,37]. Other critical impacts include access to

high-rise residential buildings, especially for vulnerable people [38]. The various concerns are summarized in Table 1.

Table 1. Summary of potential impacts of power outage.

	12–24 h	1 Day–1 Week	>1 Week
Communication	• Cellphone interruption (battery running out). • Communications for police and fire departments can be compromised.	• All kinds of communication are severely impacted, including cellphones and internet.	• All kinds of communication are severely impacted, including cellphones and internet.
Comfort	• Heating in winter in electrically heated buildings. • Electric lighting.	• Heating in winter in all-electric buildings. • Electric lighting. • Overheating in summer can significantly affect survival, especially of vulnerable people.	• Heating in winter in all-electric buildings. • Electric lighting. • Overheating in summer can significantly affect survival, especially of vulnerable people.
Food	Minimal	• Refrigerated food is damaged. • Depending on availability of dry food, food demand can become an issue.	• Depending on availability of dry food, food demand can become an issue. • Potential disruption of large-scale food supplies and availability of supply.
Water	Minimal	• Potential water interruption. • Domestic hot water can be compromised if electricity is employed to heat water.	• Potential water interruption • Domestic hot water can be compromised if electricity is employed to heat water.
Transportation	Minimal	• Limited possibility of personal transport due to potential lack of fuel in motor vehicles, etc. • Interruption of electric transportation (trains, trams, etc.), charging electric vehicles, etc.	• Individual transportation is compromised due to lack of fuel, or disruption in operation of the fuel stations. • Interruption of electric transportation (trains, trams, etc.), charging electric vehicles, etc. • Potential disruptions to public transportation.
Safety	• Indoor air quality, especially in very tightly spaced buildings or apartment buildings. • CO_2 built up in case of using alternative heating. • Access, especially for multistorey buildings.	• Indoor air quality, especially with very tightly spaced buildings or apartments/condos. • CO_2 built up in parking lots (apartment buildings with underground parking). • Access, especially for multistorey buildings (for elderly or people with health issues).	• People with electrical medical devices (heart, breathing, etc.). • Risk of shortage of supply of medicaments. • Care for emerging sickness (especially for children and vulnerable people). • Mental health effects from traumatic or stressful experiences during outages. • Post-outage hazards from sheltering in place in unhealthy environments. • Potential exposure to hazards such as contaminated drinking water, contaminated floodwaters (if flooding occurs), and potential mold growth and moisture in housing. • Environmental hazards due to damage to sewage treatment. • Health and safety risks from clean-up and recovery activities.

Table 1. *Cont.*

	12–24 h	1 Day–1 Week	>1 Week
Security	Minimal	• Financial security: ATM not working. • Risk of looting.	• Financial security: ATM not working, cash availability. • Looting. • The risk of disturbance to public order and security.
Health concerns	• People with electrical medical devices (heart, breathing, etc.).	• People with electrical medical devices (heart, breathing, etc.). • Risk of shortage of supply of medicaments (for persons requiring supply for less than a week). • Water shortages, spoilage of foods.	• People with electrical medical devices (heart, breathing, etc.). • Risk of shortage of supply of medicaments. • Care for emerging sickness (especially for children and vulnerable people). • Mental health effects from traumatic or stressful experiences during outage. • Risks to health and safety emerging from certain clean-up and recovery activities. • Water shortages, spoilage of foods.
Threat to life	• People with electrical medical devices (heart, breathing, etc.).	• People with electrical medical devices (heart, breathing, etc.). • Potential compromise of medical and social care institutions, etc. • Increased traffic accidents.	• People with electrical medical devices (heart, breathing, etc.). • Potential compromise of medical and social care institutions, etc. • Potential risk to life and health due to the occurrence of secondary crisis. • Increased traffic accidents.
Damage to dwellings' contents	• Minimal	• Potential damage from power surge after an outage to computers, TVs, air conditioners, heaters, motors, and other HVAC components. • Appliances, including washers, dryers, and microwaves, are vulnerable to sudden and frequent changes in voltage.	• Potential damage from power surge after an outage to computers, TVs, air conditioners, heaters, motors, and other HVAC components. • Appliances, including washers, dryers, and microwaves, are vulnerable to sudden and frequent changes in voltage.
Damage to dwellings	• Minimal	• Frozen pipes- bursting (in cold period). • Water damage due to pipe burst. • Potential appearance of moisture and damp patches. • Potential basement flooding and consequent damage to equipment and furniture.	• Frozen pipes- bursting (in cold period). • Water damage due to pipe burst. • Potential appearance of moisture and damp patches. • Potential basement flooding and consequent damage to equipment and furniture.

- Medium-term outage (24 h–1 week):

Beyond 24 h, some functions and human needs become difficult to fulfill. For instance, communication can be severely disrupted, including communications for police and fire departments, compromising public safety [19]. Basic levels of thermal comfort through adequate heating and cooling may become unattainable, especially during severe climate events. This can significantly affect the well-being of occupants and, in some cases, lead to the buildings' evacuation. Domestic hot water can be compromised as well if electricity is employed to heat water [39]. Similarly to the short-duration outage, people with critical electric equipment can experience life-threatening situations. In addition, medical centers and the supply of medicines can be affected, even in the presence of some emergency power generation means [19].

Other crucial issues include damage to dwelling contents such as the refrigeration of food and damage to various electrical equipment appliances such as computers, TVs,

HVAC, and various electric appliances, which can be damaged by power surges [40]. Under extreme cold conditions, other significant issues can arise, such as the bursting of frozen pipes coupled with water damage [41,42].

At the safety level, indoor air quality can be significantly impacted, especially in tight-sealed buildings that rely on mechanical ventilation [43]. In addition, carbon dioxide can build up in underground spaces, such as in parking lots (particularly in apartment buildings), which could render these areas hazardous [44] necessitating, in some cases, the evacuation or partial evacuation of the buildings. Other issues relate to access to multistorey buildings due to the restricted function of elevators (especially for vulnerable people).

Additional issues include the limited possibility of transport due to the potential of fuel shortages or dysfunctional fuel stations, as well as the impact of power outages on electric-powered transport (e.g., trams, trains) and the charging of electric vehicles, which are becoming increasingly abundant. A summary of the main issues related to various criteria and outage periods is summarized in Table 1.

- Long-term outage (>one week):

Issues that occur during a single-week power outage continue and become more severe for longer-term periods of outage [45]. Additional potentially major issues (compared to the medium-term outage) include disruption of large-scale food and water supplies and sewage treatment. During long-period outages, serious damage to buildings can occur, potentially including pipes bursting (in cold periods, as discussed above), basement flooding, and consequent damage to equipment and furniture, as well as the appearance of moisture and damp patches [19].

Other concerns include a negative impact on living standards and social services, mental health issues due to traumatic experiences, and the potential occurrence of various emergencies during the outage that might endanger health and life [46]. Hazards from sheltering in inadequate housing conditions include exposure to various hazardous conditions such as contaminated water, mold, and moisture [46]. Population displacement leads to large-scale problems, such as housing shortages, accompanied by economic and social impacts. A detailed summary is presented in Table 1.

Table 2 graphically shows the various functions and needs that are impacted by power outages, according to the time length of the outage. The main impacts are indicated by triangles. Circles indicate that a combined impact of other factors may apply. These factors include residence types, location, and demographics, as well as the type of fuel employed to power various functions (e.g., heating, appliances, etc.). Residence types include detached houses, attached houses, low-rise apartments, mid-rise apartments, high-rise apartments, and apartments with or without underground indoor parking. Locations may include urban high-density areas, rural areas with moderate density, and farmland. The demographics of the population can play an important role in the resilience of a community; this includes the existence of elderly people (couples or singles), families with vulnerable individuals (the elderly, children, etc.), and young individuals (couples or singles). Other impactful factors relate to the design of the buildings and the neighborhoods and their energy systems. While the role of building and neighborhood design is discussed below (Section 4), the impact of the other factors mentioned above is beyond the scope of this paper. These factors (building types, location, and demographics) can have a significant effect on the overall resilience of a community to power outages and need to be thoroughly investigated.

Table 2. Functions and needs that are impacted by power outage.

Period	Communication	Comfort	Food	Water	Transportation	Safety	Security	Health Concerns	Threat to Life	Damage to Dwellings' Contents	Damage to Dwellings
12–24 hours	▲▲	●●	–	–	–	●	–	●●	●●	–	–
1 day–1 week	▲▲▲	●●●	▲▲	●●	▲▲	●●	▲	●●	●●	▲	▲▲
>1 week	▲▲▲	▲▲▲	▲▲▲	●●●	▲▲▲	●●●	▲▲	●●●	▲▲	▲	▲▲▲

▲, ● Indicate low impact, ▲▲, ●● indicate medium impact, ▲▲▲, ●●● indicate higher impact. All impacts are qualitatively assessed in relative terms.

4. Technologies for Improved Resilience

There are several strategies and technologies that can be used to improve resilience during power outages at the building and neighborhood levels. Some of these are very basic and address individual needs, while some other technologies can replace the interrupted power for a specific time span. For instance, the adoption of renewable and alternative energy sources presents a practical approach to adapting to power outages associated with climate crises and extreme events, allowing it to address not only potential power interruptions and energy deficits but also to alleviate climate change-associated disruptions. Neighborhoods and communities can become more energy resilient by diversifying their energy resources, including the implementation of reliable renewable energy systems [47].

In addition to improving distributed energy generation potential, energy efficiency in buildings constitutes a key aspect of energy resilience [48,49], assisting in reducing the energy consumption of urban areas and consequently the strain on local energy suppliers during an energy emergency. Enhancing passive strategies, including passive heating and cooling, can increase the preparedness of buildings and households to withstand disasters [16,18,50]. In addition to these measures, there are some commonly applied methods, including low-tech methods, that can assist in adapting, albeit temporarily, to a power outage crisis.

This section presents an overview of various methods and strategies that can mitigate the impact of power interruptions, as discussed above. These strategies are then preliminary classified according to various criteria. The work acknowledges, however, that there is a need to analyze in more depth the potential of various technologies and to quantify their impacts on improving energy resilience.

4.1. Building-Level Measures

Some methods are commonly employed in residential buildings to cope with power outages. Most of these methods can be helpful for short timespans and to address a specific need, including emergency lighting (e.g., emergency exits, floor lighting, and other important signage). Other methods relate to energy efficiency measures that allow a reduction in the electricity load and prolong the period of building autonomy without relying on mechanical systems. This has been investigated in a large number of studies, as presented in Section 4 (see below). Other advanced methods, including those focusing on energy generation, are presented below.

Low-tech and alternative methods

Some of the temporary coping methods include simple devices that can be easily acquired and utilized for restricted needs, such as flashlights and candles to provide lighting for limited visual tasks or portable gas stoves to allow food preparation. When the crisis

lasts longer than a few hours, some basic needs start to be important to fulfill, including food preparation and thermal comfort, especially heating in cold weather. Alternative solutions such as a wood stove or wood fireplace can mitigate some of these critical issues for short- to medium-term outages [19,35]. However, these methods would not fulfill a wider range of needs and cannot be applied to all types of buildings (e.g., wood fireplaces).

For thermal comfort, an efficient building design, especially building envelopes, can assist in keeping the residence at acceptable conditions; however, these are also short- to medium-term solutions, depending on the exigency of the outdoor thermal conditions.

Energy efficiency measures

Energy efficiency plays a major role in reducing demand, especially during periods of extreme stress on the grid. For instance, extreme heat or cold events may increase in magnitude and frequency, leading to an increase in peak electricity demand [51]. Higher electricity demand can lead to prolonged power interruptions [52]. The energy efficiency of building equipment and appliances can help communities reduce their overall load and, as such, their demand on the local grid, which may assist in avoiding outage interruptions in critical periods.

Energy-efficient buildings with high-performance building envelopes allow the passive performance of buildings, leading to some level of inhabitability without the requirement of mechanical systems. For example, research carried out on some buildings in New York City to evaluate the impact of power outages on indoor temperatures in winter and summer demonstrates the better thermal resilience of high-energy-performance buildings. Such buildings that were designed with highly insulated and air-tight building envelopes maintained a comfortable indoor temperature (in the upper 50 s °F (10 s °C) in the winter during a theoretical weeklong power outage [22], while the indoor air temperature of older building types dropped to 40 s °F (4.5 °C) [53] in a period ranging from 1–3 days, causing health risks, especially to vulnerable inhabitants.

Various passive strategies can assist in reducing the impact of outdoor conditions, both high and low temperatures, on the indoor environment. The impact of building design, including the building envelope, is discussed more in the building design section (Section 4) below.

4.1.1. Energy Generation

Technologies that permit the use of renewable and alternative energy sources for power and heat production can offer resilient backups for communities [54,55]. These technologies comprise on-site generation using photovoltaic systems, including building-integrated photovoltaics (BIPVs), solar thermal collectors, geothermal heating, and micro wind turbines coupled with microgrids. The planning and implementation of such technologies can be beneficial for the whole community and particularly pertinent to critical facilities such as hospitals and buildings accommodating vulnerable people (e.g., retirement homes). Combined heat and power systems and microgrids can operate continuously (not only during emergencies) and, as such, they present reliable methods of energy supply.

PVs Coupled to Batteries

PV systems can withstand extreme weather events, providing backup power for buildings and critical facilities, thus enhancing the resilience of communities [29]. PV systems can be sized to provide the most critical functions to residences to survive power outages [56]. Buildings with hybrid photovoltaic–battery storage systems can provide a continuous electricity supply during power outages, depending on the weather conditions and the battery size as well as the building energy load [57]. Research highlights that a combination of PVs, battery storage, and grid connections is cost-effective and environmentally efficient [58].

The potential of PVs coupled to batteries has been investigated in a number of studies [16], including the capabilities of PVs and plug-in hybrid electric vehicles to enhance the resilience of households [59] and their return on investment [60]. The impact of a PVs–batteries combination on the resilience of whole communities was also studied, e.g., [61,62].

Micro Wind Turbines

Small-size urban wind turbines include building-integrated wind turbines or small stand-alone wind turbines [63]. Building-integrated wind turbines can be grid-tied or off-grid, requiring battery storage to store energy. The rotor diameter of residential wind turbines can range from 0.9 m to 7 m and require a height of 18 m to 30 m [64].

Wind turbines extract about 40–50% of the energy that passes through them [65]. A traditional single-home family would need one 10–20 KW turbine to produce sufficient energy to fulfill the total energy demand of a typical house (using approximately 10,000 kWh per year) [66].

The feasibility and efficiency of wind energy depend mainly on the location. Wind turbines are more suited for areas with reduced obstacles and with an average annual wind speed of at least 10 mph (16 km/h) [67].

Micro Combined Heat and Power

Micro combined heat and power (micro-CHP) is a heat and power cogeneration system designed for use at the building scale, such as single or multi-family houses, and can also serve small office buildings (up to 50 kW [68]). A micro-CHP system provides electric power while simultaneously generating thermal energy for space heating and hot water provisions for a building by recovering waste heat [69].

A micro-CHP system can be designed to follow the electricity or heat demand of a building, delivering heat or electricity as a by-product. This may result in the production of excess electricity or heat, which requires devising methods to manage the excess power, such as designing storage systems [70]. Excess electricity can be, under regular circumstances, fed to the grid.

The most common micro-CHP systems employ natural gas to cogenerate heat and power. Although natural gas CHP is responsible for GHG emissions, due to the effective efficiency of the CHP system, the produced emissions are less than those of other alternative systems for generating heat (e.g., a condensing boiler) [71].

Although connected to the electricity distribution network, CHP systems, including micro-CHPs, can be completely independent, allowing them to produce energy when it is required, thus improving the resilience of a building to power interruptions.

Fuel Cells

Fuel cell technologies present a promising option for clean power generation. This technology allows the generation of electrical energy while producing heat as a useful by-product. Fuel cells convert energy into electricity and heat through the chemical reaction of hydrogen and oxygen to produce water [72,73]. Although fossil fuel is generally used to produce hydrogen (the basic ingredient of fuel cells), fuel cells create significantly fewer emissions than most other fossil fuel generators [72].

Fuel cells are mainly employed in two major applications: powering vehicles and generating power for various types of buildings, utilities, and communities. Demonstrated applications of fuel cells include backup generation for hospitals, office buildings, and schools [74]. Some applications include remote villages and campgrounds [75]. Fuel cells can also be used to supply power for temporary needs, including shelters and construction sites. Fuel cells can play a significant role in enhancing distributed energy initiatives, providing electricity and heat, and reducing the vulnerability of central grid disruptions.

Integrated Micro-Generation Systems

Integrating different systems and methods to generate heat and power is continuing to attract attention to improve the efficiency of renewable and alternative energy resources. For instance, research on the integration of a fuel cell (FC) micro-cogeneration device, a heat pump (HP), and thermal storage highlights that such a combination presents an optimal solution to manage electrical and thermal storage while reducing energy consumption and

evading energy excess production, e.g., [69,76]. An FC-based CHP system can be sized to produce sufficient energy for individual buildings.

Other research investigated the integration of heat pumps, PV systems, and the local grid connection, demonstrating the efficiency of such systems in multistorey buildings [77].

Portable Generators with Various Fuel Types

Generators are some of the most common systems to generate distributed energy. The fuel employed in generators ranges from high-GHG-producing, such as diesel generators, to natural gas (NG) [78]. Although NG generators are cleaner than diesel generators, they still have high GHG emissions. Other generators use gasoline and propane as fuel. Gasoline-fueled generators fall between diesel-fueled and natural gas generators in terms of GHG emissions, while propane generators are similar to natural gas generators (in terms of emissions).

Employing such generators can be useful during an emergency power interruption; however, they should be restricted to use as emergency back-up generation. Emission-control measures should be put in place when such power generation methods are employed to reduce their harmful environmental impacts. These measures comprise improvements in fuel and control technologies and enhanced efficiency.

4.2. Neighborhood-Level Energy Resilience

Most of the energy generation technologies suitable at the individual building level can be effective on a neighborhood level, with design modifications to suit larger-scale developments. For example, PV systems and wind turbines can be designed to be not only part of a building (integrated within the building envelope or add-on systems) but also part of the neighborhood outdoor surface (see Section 4). Similarly, wind turbines can be installed in various areas of the neighborhood. A CHP plant can be designed more efficiently at the urban scale, as discussed below. Additional technologies that can be applied only on the urban scale include district heating and cooling systems, microgrids, and smart grids. These are summarized below.

4.2.1. Combined Heat and Power

Urban- and community-level CHP systems serve the same function as a micro-CHP (described above) but are designed at a larger scale to serve multiple buildings within a neighborhood. Examples of CHP implementation and its performance and impact during power outages due to weather events are reported in the literature [79]. For instance, during Hurricane Sandy, CHP systems supplied heat and power (although sometimes in limited capacity) as well as other critical functions to multifamily buildings [54]. Maintaining critical services during a power outage is vital to improving the overall resilience of communities and can affect multiple households. This is because the risk to individual buildings and individuals can be significantly reduced by keeping vital services running (hospitals, water treatments, and others). On the other hand, designing such critical buildings and facilities with backup power can enable them to serve as temporary shelters for displaced residents [80], leading to increased social resilience and capacity to cope.

CHP systems can use various types of fuel to provide continuous operations. Most CHP systems are fueled by natural gas, which can be reliable during outages (as long as natural gas pipelines are not disrupted). CHP can be operated using waste generation biomass or biogas, which can be equally reliable in times of disaster [54]. In addition to providing emergency power, CHP systems are cost-effective and reduce overall net emissions [81].

4.2.2. District Energy

District energy systems can integrate several types of renewable energy sources to produce thermal and electrical energy [82,83] while reducing GHG emissions [84]. Some of the most common renewable sources incorporated in district energy systems include solar photovoltaics and stand-alone microgrids, as discussed below. Biomass is also used in some communities using local waste generated from tree trimming and other urban

waste wood. These technologies are often coupled with electrical and thermal energy storage (e.g., batteries [85], fuel cells [86,87], and borehole geothermal energy storage [88]). The integration of different energy sources constitutes an effective method to enhance the efficiency of the entire system.

District energy systems can be designed to fulfill only one requirement, such as heating, cooling, combined heating and cooling needs, co-generation, or tri-generation [83]. District systems allow the shift in energy consumption from peak demand to off-peak periods, thus reducing the dependence on the electric grid.

4.2.3. Microgrids

The microgrid concept is explained employing a number of definitions [89–91]. Most commonly, a microgrid is defined as a mix of distributed energy resources and interconnected loads, constituting a single controllable entity that can be connected to or disconnected from the grid. When disconnected from the grid, the microgrid can operate in island mode [92].

Microgrids connect buildings and facilities within a neighborhood to various distributed energy resources, such as those described above (e.g., CHP, photovoltaic systems, wind turbines, district energy systems, and energy storage). The design of a microgrid system varies depending on the project specifications and requirements [89]. Microgrids can play a key role in enhancing the resilience of communities against power outages since they are able to maintain a reliable and continuous supply of power.

4.2.4. Smart Grid

Smart grids are advanced digital systems that enable a two-way power flow [93] and incorporate several technologies, comprising advanced metering and information and communication networks, which are integrated into power infrastructures [94]. Smart grids can use different energy resources, including intermittent solar- and wind-generated electricity [95], and can accommodate storage facilities. Smart grids can play a significant role in restricting the spread of power outages since they allow the identification of the impacted parts of the electricity system and can then isolate them, improving the resilience of a community to the power outage. Smart grids also allow users to preventively turn off the power in specific areas before extreme weather events to avoid system-wide damage. This capability assists in reducing the extent of power outages and shortening recovery times.

Overview of Technologies' Potential

This section gives an overview of the potential of the technologies presented above with respect to a number of criteria. These criteria include the current feasibility of these technologies and their environmental impact, including their efficiency (Table 3). The potential of these technologies is presented in a qualitative manner (Table 4), indicating the fulfillment of some of the criteria.

Table 3. Description of criteria.

Feasibility:	**Building types:** potential to accommodate variety of buildings. **Accessibility**: relates to various issues such as availability on the market, cost, etc. **Implementation:** relates to the ease of implementation in a building, ease of use, etc.
Impact	**Reduced Emissions**: potential to reduce GHG emissions (based on materials used or/and fuel consumed). **Efficiency**: increase in the value of reduced damage from power breakdown (fulfillment of the objectives) to investment in the technology.
Objectives	**Comfort:** achieving survivable and safe temperatures and acceptable overall comfort (e.g., lighting). **Indoor air quality:** potential improvement in indoor air quality. **Health and safety:** potential reduction in health and safety hazards. **Fulfilling specific need:** potential to fulfill various needs (more than one). **Continuous power generation:** potential to generate stable power.
Outage Period	Describes the suitability of the resilience measure to the outage time.

Table 4. Summary of technologies potential. ● indicates fulfillment, ▲ indicates unfulfillment, S: short-term, M: medium-term, L: long-term.

	Feasibility			Impact		Objectives					
	Accessibility	Implementation	Building Types	Reduced Emissions	Efficiency	Thermal Comfort	Indoor Air Quality	Health and Safety	Fulfilling Other Needs	Continuous Power	Outage period
Low-tech and alternative measures											
Candles, flashlights, propane/kerosene lamps	●	●	●	●	▲	—	▲	▲	▲	—	S
Wood stove	▲	▲	▲	●	▲	▲	▲	▲	▲	—	M-L
Portable gas stove	●	●	●	▲	●	—	▲	▲	▲	—	S-M
Wood fireplace	▲	▲	▲	●	▲	▲	●	▲	▲	—	M-L
Batteries	▲	●	●	●	▲	—	—	—	●	●	S-M
Efficiency measures											
High-performance building envelope	▲	▲	●	●	●	●	●	—	▲	—	S-M
Passive solar design	▲	▲	●	●	●	●	●	—	▲	—	S-M
Operable windows/natural ventilation	▲	▲	●	●	●	●	●	—	▲	—	S-M
High-efficiency appliances	▲	●	●	●	●	—	—	—	—	—	M-L
Generation											
PV	▲	▲	●	●	▲	●	●	●	●	▲	S-L
Micro wind turbines	▲	▲	●	●	▲	●	●	●	●	▲	S-L
Micro combined heat and power	▲	▲	●	▲	●	●	●	▲	●	▲	S-L
Portable generators/propane/diesel	▲	▲	●	▲	●	●	●	▲	●	●	S-L
Fuel cells	▲	▲	●	●	●	●	●	●	●	●	S-L
Neighborhood level											
PV	●	▲	●	●	▲	●	●	●	●	▲	S-L
Wind	●	▲	●	●	▲	●	●	●	●	▲	S-L
CHP	●	●	●	▲	●	●	●	●	●	●	S-L
District energy	▲	▲	●	●	●	●	●	●	●	▲	S-L
Microgrid	▲	▲	●	●	●	●	●	●	●	●	S-L
Smart grid	▲	▲	●	●	●	●	●	●	●	●	S-L

5. Impact of Building and Neighborhood Design

This section is based on the author's research and aims to illustrate the implementation of principles outlined in the literature review of Sections 2 and 3 in the design of buildings and neighborhoods and their energy systems to improve their overall energy resilience. The section highlights the impact of a holistic approach in the design of neighborhoods, their buildings, and the exterior areas surrounding the buildings in order to provide an adequate environment for implementing measures to enhance energy resilience and empower the neighborhoods' residents.

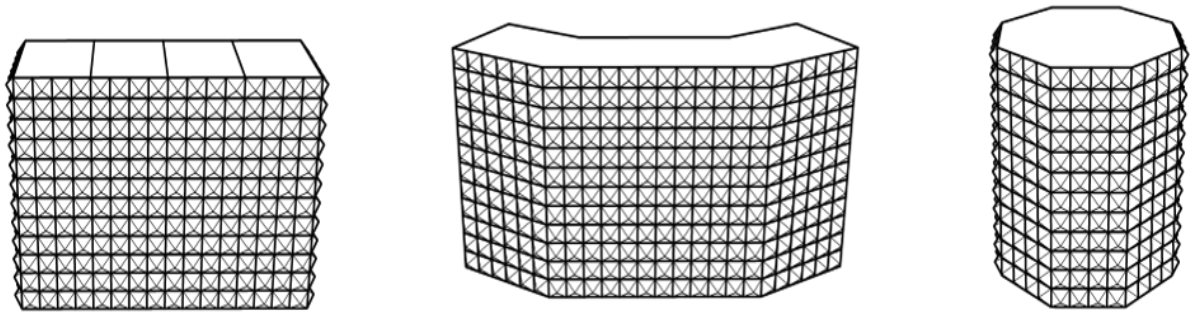
5.1. Building Design

The design of a building significantly affects its energy efficiency, its capability to withstand climate events, and its vulnerability to energy outages. Design considerations, such as the building type, form and configuration, and outer envelope, directly affect the building's energy demand [18,22,96] and its potential to incorporate solar technologies for sustainable energy production. Improving such capacity is, as mentioned above,

a significant strategy to mitigate the impact of central power interruptions. Design aspects, such as being highly insulated, having an airtight building envelope, and having optimized window systems with an adequate window-to-wall ratio (WWR), can significantly impact the energy requirements of a building. The window-to-wall ratio (WWR) is a variable parameter, and a country's building and high-energy performance codes govern the appropriate WWR value. Some examples of high-performance windows are thermochromic glazing [97] and ventilated/non-ventilated PV-integrated windows [98]. These high-performance windows significantly diminish heating and cooling requirements while improving visual and thermal comfort. This is not only beneficial in reducing the size of mechanical equipment but also in increasing the duration of the self-sustainability of a building without relying on electric energy to provide these functions. The design of various other climate-responsive features and architectural passive design elements, including shading strategies, light shelves, and solar chimneys, can maximize the utilization of solar energy for heating, cooling, and daylighting, reducing dependence on local energy grids. Architectural passive design features can be implemented in different types of buildings, including residential, office, and commercial, allowing the enhancement of buildings' adaption to energy interruption.

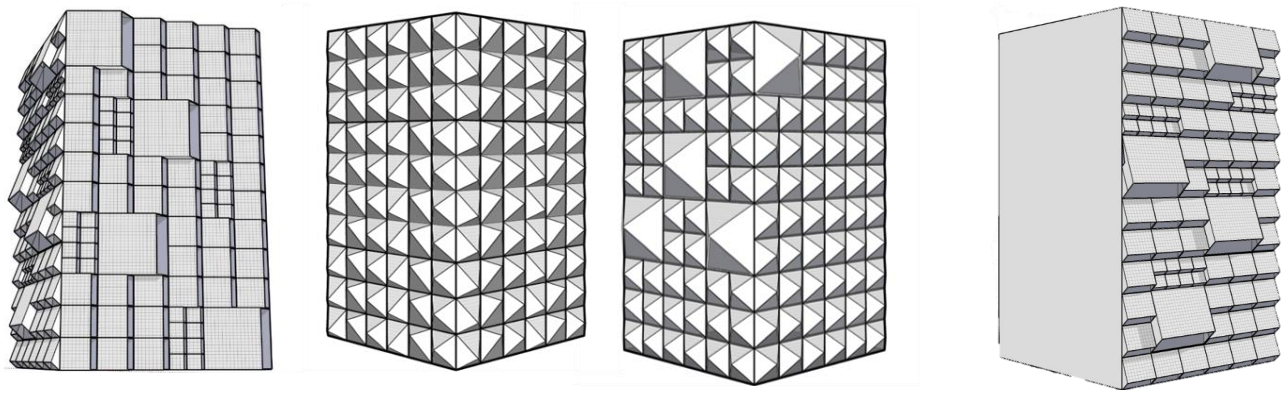
Building envelope design for energy generation. The design of the building envelope plays a significant role in preparing buildings to integrate renewable energy generation technologies (e.g., PV and PV/thermal systems (PV/T)), thus improving their potential to withstand power outages. The shape of the building and of the envelope affects its solar exposure and thus its solar potential, which is highly dependent on the tilt and orientation angles of these surfaces (Figure 1 [99]). While integrating PV technologies in roofs is an optimal decision for low-rise buildings ($\leq$3 floors), multistorey buildings' facades can offer advantageous surfaces for the integration of PV systems due to their increased surface area from the increased height of multistorey buildings relative to the roofs of the same buildings (which remain unchanged [100]).

The geometric design of building envelope can be carefully designed to maximize solar radiation incident on these surfaces, consequently increasing the electric and thermal energy generated by solar collectors. Manipulating the tilt and orientation angles of individual building surfaces can lead to increased electricity generation and the extension of the timing peak generation. Multifaceted geometry (Figure 3d–f) can significantly increase the energy generation potential of roofs and particularly facades [100]. Such design considerations can provide the creative assimilation of PV systems, making them architecturally and esthetically pleasant.



(**a**) (**b**) (**c**)

Figure 3. *Cont.*



(**d**) (**e**) (**f**) (**g**)

Figure 3. Design of buildings for enhanced solar potential: (**a**–**c**) building layout, (**d**–**g**) building facades.

5.2. Neighborhood Design

Neighborhood design has a significant impact on the energy consumption and GHG emissions of the overall neighborhood and enhances its resilience and capability to adjust to different stresses. Below is a summary of some factors that should be considered in the design of resilient communities and neighborhoods.

Type of neighborhood and building mix. A mixed-use neighborhood that encompasses diverse amenities within walking distance provides several possibilities for mitigating energy vulnerabilities. For instance, such neighborhoods can reduce the dependence on vehicle transport when fuel is restricted and can provide potential nearby temporary shelter in buildings that can be supplied with continuous alternative energy (e.g., schools [80]). Other opportunities offered by mixed-use neighborhoods include the prospective application of district energy, large-scale renewable energy, thermal storage, and energy sharing between buildings.

The variety of building types within a neighborhood can affect its energy consumption as well as its overall capacity to accommodate solar technologies within its buildings and neighborhood surfaces [101]. An optimal ratio of commercial to built land area ranges from 23% to 32%, allowing for a reduction in energy consumption and GHG emissions.

The mix of buildings also affects, as mentioned above, the potential of designating specific buildings as temporary shelters during power outages. Figure 4 presents an example neighborhood that includes various amenities and buildings that can serve as temporary shelters, which are strategically placed with respect to roads and residential buildings [80].

Designated temporary shelters can be selected, where possible, according to their energy intensity, prioritizing those that have a reduced overall energy intensity (energy per unit area) or emergency power generation capacity. In addition, such buildings should be easily accessible to the residents of different parts of the neighborhood.

Density. An increased built density, including a high ratio of built floor area in a neighborhood, is often associated with urban environmental sustainability [102]. To augment the potential of renewable solar energy generation, enhancing solar availability is a high priority. The solar access of buildings and the neighborhoods' outdoor areas can be negatively affected by high density, especially with the design of high-rise multistorey buildings. The impact of density on solar access can be offset through the thoughtful design of the urban layout, site coverage, and building heights [103,104]. Increasing spacing between buildings allows better solar access to buildings and increases solar availability at the ground level for the implementation of standalone PV systems for neighborhood-level electricity generation (see below). On the other hand, while low-density residential neighborhoods can achieve energy self-sufficiency from PVs integrated into buildings' surfaces, higher-density neighborhoods require diverse energy sources that are combined with energy storage [101]. A study that investigated and contrasted the energy resilience of

low- and higher-density neighborhoods based on specific resilience indicators showed that higher-density, mixed-use neighborhoods are less energy resilient [80].

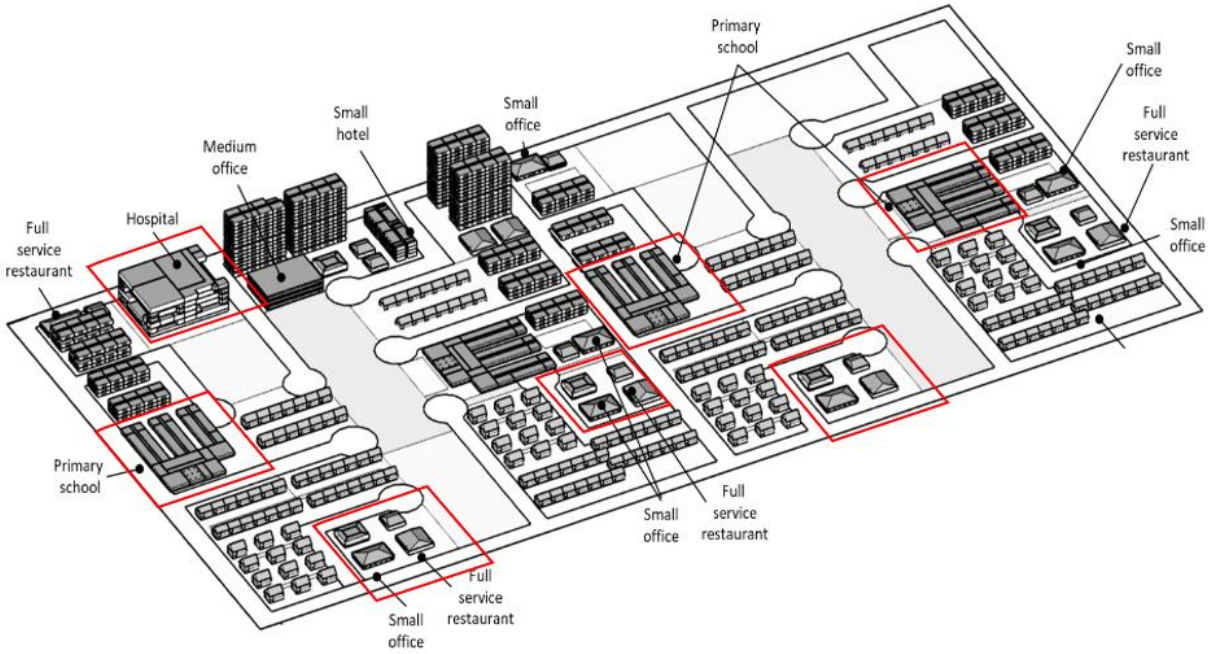


Figure 4. Example of mixed-use neighborhood with various amenities. Red lines indicate buildings that can serve as temporary shelters, and/or buildings that need to maintain continuous operations.

Green and spatial areas. Landscape and outdoor areas surrounding buildings can be designed to maximize the incorporation of PV and solar thermal collectors within neighborhoods (Figure 5a). For solar applications, the design of public green areas should address various issues such as avoiding shade from surrounding buildings.

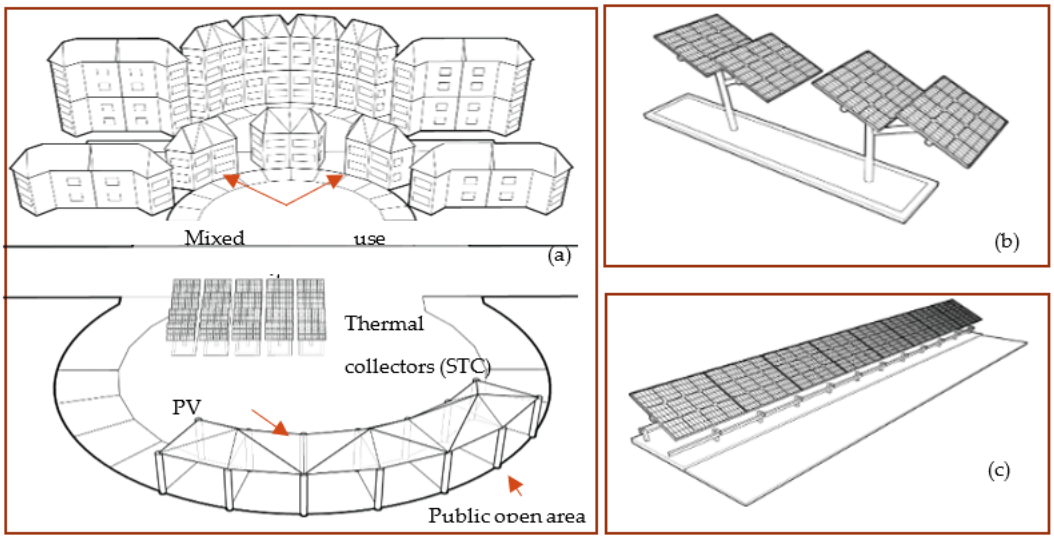


Figure 5. (**a**) PV and STC integration in public areas, (**b**) PV as parking structure, (**c**) PV on street borders.

The implementation of solar collector structures in the public landscape can be designed to enhance outdoor thermal comfort, creating attractive areas for social interaction and, as such, improving the quality of life in the community. For example, landscape PV structures can be employed as shading structures for thermal shelters during colder periods (Figure 5b,c).

Street design. The street layout, including shape and orientation, influences the design and orientation of the buildings on them. Street design therefore has an impact on the solar potential of the surrounding buildings.

Beyond their impact on the energy consumption and energy generation of the buildings and surrounding areas, the street's design has a significant impact on the choice of transport and resulting energy consumption and GHG emissions. Research highlights that streets with a higher density of intersections may decrease the reliance on individual cars for transportation [103].

The design of connection nodes and available routes affects the potential for evacuation during emergencies and therefore impacts the resilience of the whole community. A key criterion for creating resilient neighborhood layouts is to reduce dependence on major streets. This design consideration prevents the destabilization of the entire street network system when some central nodes are disabled due to power outages or climate-related events [100]. Potential shelter buildings should be located at street intersections to improve their access during evacuations [80]. Although analyzing the response to disasters is beyond the scope of this paper, the impact of neighborhood design on some responses (such as evacuation) is mentioned due to the interconnection of various design elements and their direct and indirect impacts on energy resilience.

5.3. Impact of Design on Energy Systems

Resilient neighborhood design should consider energy demand as well as local and distributed energy generation strategies. The impact of neighborhood design on urban energy systems, both on the demand and supply sides, is briefly discussed below.

Energy demand. Energy demand can be significantly reduced through the architectural design of buildings and proper spatial neighborhood design. Employing high-energy-performance mechanical systems and energy-efficient appliances can further reduce energy consumption in buildings. Efficient mechanical systems, including heat pump technologies, heat pumps coupled with PV systems, heat recovery systems, mechanical ventilation (e.g., displacement ventilation), and effective distribution and controls, are increasingly implemented to improve the energy performance of different building types. For instance, smart management systems can be implemented to preheat or precool buildings before peak hours [105,106]. The deliberate exploitation of thermal mass, together with energy-efficient building envelopes and mechanical ventilation, can assist in the strategic preheating and precooling of buildings [107].

Other promising systems consist of ground source heat pumps (GSHPs), which, using ground-extracted heat, are considerably more energy-efficient than conventional mechanical systems [108]. Coupling a GCHP system with solar thermal collectors offers a significant opportunity for energy savings, especially for heating-dominated neighborhoods [109]. Integrating energy efficiency measures with microgrid technology allows for a reduction in energy demand on the microgrid itself.

Energy supply and neighborhood planning. Diversification of energy resources constitutes a promising strategy to enhance the energy resilience of a community. PV technologies integrated in buildings and in neighborhood outdoor areas form a mature technology that is ready to be deployed at various scales and capacities [110], forming an important layer of energy resilience. Together with solar technologies (PV and STC), other energy resources, including combined heat and power utilizing various sources, such as waste to energy (WtE) or reduced impact fuel (see above) and small wind turbines, can be explored, especially when available surfaces for installing solar systems are restricted. To achieve self-sufficient neighborhoods, energy storage is required, together with an optimal mix of energy sources [101]. To be completely independent from the grid, during an energy crisis, electrical and thermal storage should be sized to provide the necessary demand of a neighborhood. It should be considered that increased levels of distributed energy resources may lead to issues in energy balance and congestion. These potential congestion

issues should be addressed when designing urban energy systems, allowing for the proper management of energy production, utilization, control, and storage.

On the other hand, microgrids and smart metering can be beneficial in controlling the zones that can be supplied with energy at specific times. For instance, a study carried out by Singh and Hachem-Vermette [77] shows that, for long periods of power interruption, it might be beneficial to evacuate the population to designated temporary shelters (e.g., schools) and to prioritize these buildings when supplying local energy. Such a scenario will be less vulnerable than sheltering in place, as it is easier and more efficient to supply a few buildings with energy rather than a larger number of residences. In such cases, smart grids can be useful in controlling the energy supply to specific zones.

6. Discussion and Conclusions

This work presents an overview of the impact of power interruptions on buildings, buildings' occupants, and neighborhoods. It also discusses the existing technologies, ranging from simple to more advanced, to mitigate some of these impacts. The paper finally highlights the role of building and neighborhood design in resilient energy systems.

Depending on its length, a power interruption can severely impact people, buildings, and neighborhoods. These impacts may include threat to the lives of vulnerable populations, even under short-term power interruptions, while, at a longer term, other issues can arise, including displacement of the population, serious damage to buildings, and instability of neighborhood organization. The severity of the power interruption impact is enhanced by the interconnection of energy systems with many other basic systems, such as water, food, connectivity, and transportation systems. The gravity of power interruption impacts can be affected by various factors, including demographics, building type, building design, and location. Research focusing on highlighting the correlation between the severity of power interruptions and the factors mentioned above is still lacking.

There are various methods to cope with power interruptions at building and neighborhood levels. At a building level, some of these methods are simple and affordable, allowing the fulfillment of a specific need for a short time, while others are more sophisticated and need planning and a larger budget to be efficiently implemented. Such methods include PV-integrated systems with battery storage or integrated wind turbines. Several strategies need to be analyzed with respect to the building type to fully understand their potential and feasibility. For example, a wood stove cannot be easily installed in a multistorey building if it is not designed at an early stage. On the neighborhood level, the implementation of technologies requires more advanced planning, involving various stakeholders. Although some single technologies, such as neighborhood PV installations or combined heat and power (CHP), can mitigate power interruption, research shows that the integrated design of various renewable and alternative energy sources within smart microgrids presents more efficient and low-environmental impact solutions. Other employed and relatively easy-to-implement solutions such as generators, including portable ones, should be limited to emergency back-up generation. The utilization of such methods should be governed by emission-control measures to reduce harmful environmental impacts.

On the design side, a holistic approach should be applied in planning energy-resilient neighborhoods. This approach depends on the integration of building and urban design considerations, as well as on the interaction between these design considerations. Buildings and surrounding open public spaces need to be considered active elements of the energy network, contributing to production, storage, and supply. The various components of a neighborhood should be planned to maintain uninterrupted operation and to maximize their energy efficiency and potential contribution to the neighborhood energy system. For example, street layouts can be designed to allow the optimal orientation of the surrounding buildings while ensuring functionality during disruptions, thus enhancing the overall operation and resilience of the neighborhood. Additionally, the thoughtful consideration of building density assists in achieving a range of economic, social, and environmental benefits without compromising the solar potential of open public spaces and building surfaces.

A flow chart presenting the main research output is included below (Figure 6).

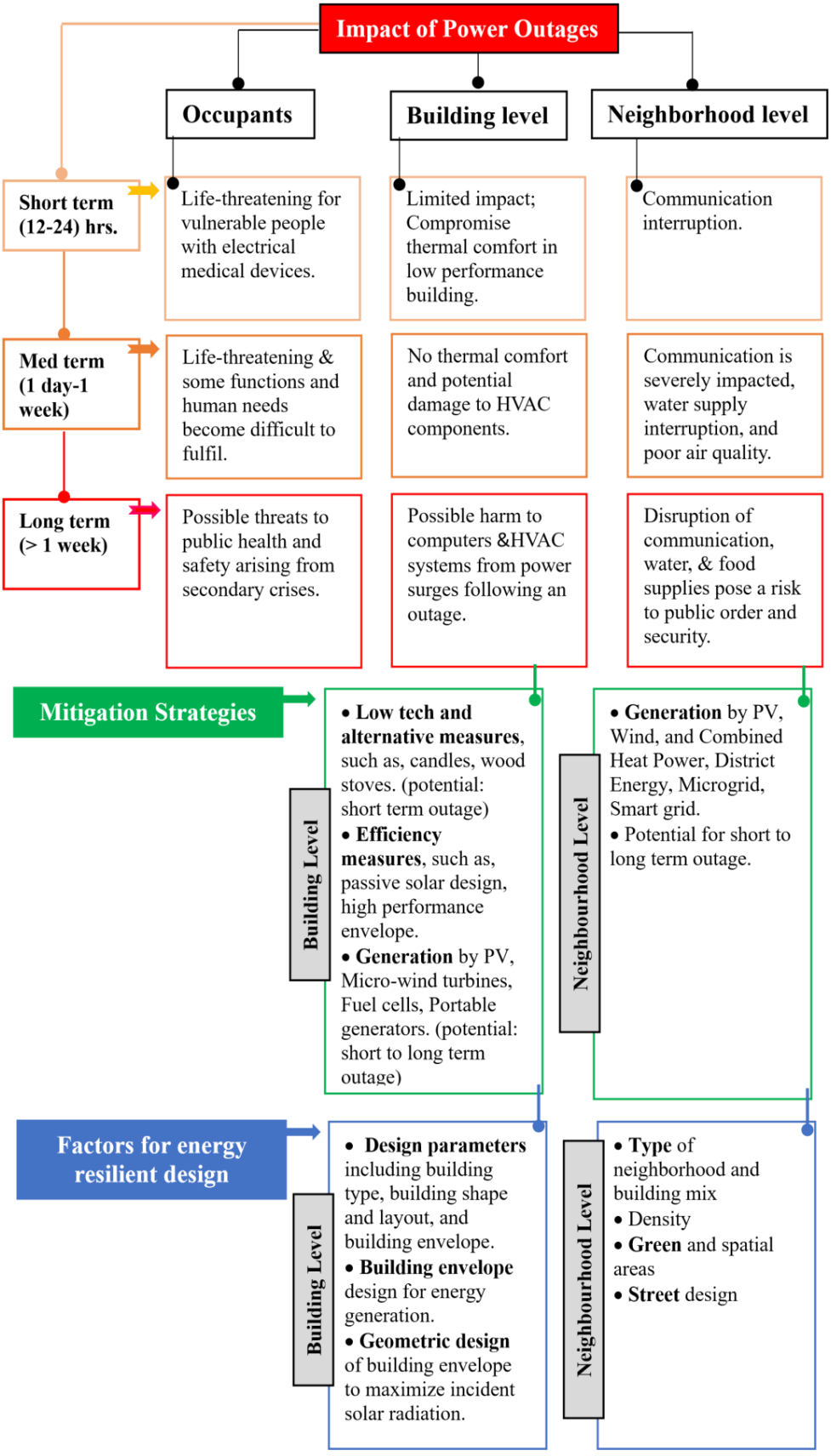


Figure 6. Flowchart of main research output.

The strategies and technologies discussed in this work can assist in minimizing the impact of power interruptions and ensuring a reliable energy supply. This can contribute to fulfilling several of the SDGs. For example, developing and implementing microgrids and promoting the use of renewable energy sources and energy storage technologies can reduce dependence on a single energy source (usually the local grid), contributing to SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action). Reducing energy consumption through the implementation of various energy efficiency measures reduces resource consumption and waste generation, promoting responsible consumption (SGC 12). In addition, a resilient and uninterrupted energy supply is vital for vulnerable people (with health issues) and for healthcare facilities, ensuring continuous access to medical services during climate disasters (SDG 3: Good Health and Well-being). Other indirect contributions of this work to the SDGs include encouraging the development of innovative solutions to mitigate power interruptions and to improve the robustness and efficiency of infrastructure. This can foster economic growth and industrial development, thus supporting SDG 9 (Industry, Innovation, and Infrastructure).

Conclusions

This paper gives an insight into the impact of power interruptions and mitigation strategies and the role of neighborhood composition and building types in increasing the energy resilience of a specific neighborhood.

The review of potential issues caused by power interruptions highlights the need for substantial research to be conducted in various domains. This includes determining correlations between the severity of impacts and the parameters representative of the built environment and the population, as well as the assessment of various technologies with respect to useful criteria. In addition, investigating the impact of power interruptions and their length on the psychological performance of the population is still lacking. Such work can assist municipalities and governmental agencies in fully understanding the impact of power interruption in specific communities and, accordingly, in adopting feasible and effective mitigating strategies, as well as emergency response and management.

This review of the severe and diverse impacts of energy interruptions that span social, economic, and environmental domains supports the importance of a serious and urgent commitment to achieving the Sustainable Development Goals, as many of these goals have direct or indirect impacts on reducing the vulnerabilities of cities. Additionally, the discussed energy and design strategies can play a key role in achieving affordable and clean energy, sustainable cities and communities, climate action, and responsible consumption, among others, which are central to numerous SDGs.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

ATM	Automated teller machine	NG	Natural gas
CHP	Combined heat power	PV	Photovoltaic
CO_2	Carbon dioxide	PV/T	Photovoltaics thermal
FC	Fuel cell	STC	Solar thermal collector
GHG	Greenhouse gases	SDG	Sustainable Development Goals
HP	Heat pump	WWR	Window–wall ratio
HVAC	Heating, ventilation, and air conditioning		

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