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Towards Extensive Definition and Planning of Energy Resilience in Buildings in Cold Climate

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Abstract: The transition towards a sustainable future requires the reliable performance of the building's energy system in order for the building to be energy-resilient. "Energy resilient building in cold climates" is an emerging concept that defines the ability to maintain a minimum level of indoor air temperature and energy performance of the building and minimize the occupant's health risk during a disruptive event of the grid's power supply loss in a cold climate. The aim is to introduce an extensive definition of the energy resilience of buildings and apply it in case studies. This article first reviews the progress and provides an overview of the energy-resilient building concept. The review shows that most of the relevant focus is on short-term energy resilience, and the serious gap is related to long-term resilience in the context of cold regions. The article presents a basic definition of energy resilience of buildings, a systematic framework, and indicators for analyzing the energy resilience of buildings. Terms such as active and passive habitability, survivability, and adaptive habitable conditions are defined. The energy resilience indicators are applied on two simulated Finnish case studies, an old building and a new building. By systematic analysis, using the defined indicators and thresholds, the energy resilience performance of the buildings is calculated and compared. Depending on the type of the building, the results show that the robustness period is 11 h and 26 h for the old building and the new building, respectively. The old building failed to provide the habitability conditions. The impact of the event is 8.9 °C, minimum performance (P_{min}) is 12.54 °C, and degree of disruption (DoD) is 0.300 for the old building. The speed of collapse (SoC) is 3.75 °C/h, and the speed of recovery (SoR) is 0.64 °C/h. On the other hand, the new building performed better such that the impact of the event is 4 °C, P_{min} is 17.5 °C, and DoD is 0.138. The SoC is slow 3.2 °C/h and SoR is fast 0.80 °C/h for the new building. The results provide a pathway for improvements for long-term energy resilience. In conclusion, this work supports society and policy-makers to build a sustainable and resilient society.

Keywords: long term; energy resilience of buildings; definition; framework; indicators; energy crisis; cold climates

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1. Introduction

The United Nation's Sustainable Development Goals (SDGs) aim at achieving energy-related goals such as good health and well-being (SDG3), affordable and clean energy (SDG7), sustainable cities and communities (SDG11), and climate action (SDG13). Urban areas and buildings would play a big role in achieving these goals in the transition towards a sustainable future. Around two-thirds of the global primary energy is used in urban areas and buildings as 50% of the world's population lives in cities and urban development [1]. It is projected that 68% of the world population would live in urban development by 2050 [1]. The increase in the population in the urban areas puts additional pressure on our natural resources, particularly the energy sources [2]. To address this, there is an increase in interest and investment in energy generation by renewable sources, storage, and energy infrastructure. However, to protect this infrastructure and investments in the future cities, especially the buildings need to be smarter and more energy-resilient to withstand climate (natural)-related challenges, environmental catastrophes, economic crises, energy crises, and human-induced crises (such as policy, war etc.). This resilience must be for the short and long terms when the buildings and urban plan change with the environment; therefore, smartly adaptable buildings are needed. Building performance is calculated based on local standards, regulations, and assumptions. Multiple challenges can be faced by a building and its energy system (such as renewable generation sources) during its lifetime because of numerous changes in the environment such as climate change, economic conditions, and build environment-related policy. All these changes and events can disrupt the normal operation of the building and energy system as planned and designed. These changes and disruptions such as power outages (power loss), degradation in the building envelope, changes in the building environment, changes in the occupant behavior, etc., are usually not considered during the planning and designing phase of the building [3–5]. The building performance, renewable energy system, and demand are hugely impacted by the climate conditions and disruptive events. It is important to mention that a building's physical structure may not be directly impacted by such disruptive events (such as floods, storms, etc.); however, in this article, the disruption event refers to the impact on the grid, such as power outage that can directly impact the building energy performance.

Understanding the connection between climate-related events on the building energy performance and energy system performance is complex, uncertain, and multivariate due to complex workflows [6]. All these uncertainties and failure to address these challenges can cause power outages and a reduction in the building's energy performance. Analitis et al. conducted a comprehensive study to investigate the short-term effects of cold weather on mortality in 15 European cities [7]. The findings revealed that a 1 °C drop in temperature was linked to a 1.35% increase in the daily number of total natural deaths. Moreover, increases of 1.72%, 3.30%, and 1.25% were also observed in cardiovascular, respiratory, and cerebrovascular deaths, respectively, with a more pronounced impact noted in the older age group. The yearly cost due to the storms-related power outages in the United States of America is around 20 to 55 billion dollars [8]. Around 80% of the power outages occurred due to extreme weather between 2003 and 2012 in the United States of America (USA) [9]. The ice storm also affected the United States of America, with over 4 million people left without electricity and heating [10] and a USD 1 billion dollars loss [9]. Wu et al. conducted a case study on the February 2021 winter storm in Texas, employing multisource data to investigate the interplay between human activities and the power system during extreme weather [11]. The historic snowstorm brought snow, freezing rain, and unprecedented cold, causing catastrophic impacts, including power grid failures; over 4.5 million households faced prolonged blackouts, emphasizing the vulnerability of infrastructure and societal systems to extreme weather events. Chang et al.'s study [12] conducts an analysis of the 1998 Ice Storm in Canada using empirical data, emphasizing failures in power transmission systems that transformed a weather disaster into a technological one. This cold wave left millions without power for varying durations, leading to 30 deaths and incurring substantial economic costs estimated at 1.7 billion Canadian dollars for the Canadian government. In addition to the climate-related disruptive events, political-related issues such as war can also cause energy crises, resulting in the disruption of the grid [13]. It was observed that during winter of 2023 in extreme cold spells in Ukraine, there was power outage due to attacks on the power grids causing energy loss in the buildings (for heating). This caused losses in human life, the economy and displacement [14] due to grid loss and cold conditions inside the buildings. The extent of change in the building's energy performance due to extreme temperatures under power outage has to be analyzed. It is also vital that the transition towards a sustainable solution requires an adequate consideration of disruption to ensure the reliable minimum performance of the building's energy systems in the long run to support the buildings' occupants' comfort and habitability. This is important because a large amount of human time is spent inside the building, and resilient building performance is important for well-being. Study shows that 87% of the time is spent indoors by occupants in many developed countries [15], and occupants' thermal comfort and well-being is an essential service that a building must provide. Moreover, economic value is created inside the buildings by the humans, which is important for society.

Energy-resilient building is an emerging concept that is increasingly used to represent the stable performance of buildings during power outages caused by extreme climatic-related events such as fire, extreme temperature storms, heavy rain, coastal erosion, and earthquakes. Most of the work has focused on energy flexibility, energy resilience of the electrical grids, and resilience as a broader concept and not considering the energy resilience of the building. Moreover, the earlier studies conducted on energy-resilient building are focused on short-term resilience [16–18], which focuses on a single event and one disruption cycle. Therefore, a broader framework is needed that also discusses long-term resilience where the cascade effects and multiple cycles are considered during the lifetime of the building.

The method used in the article is reviewing the state-of-the-art literature and analyzing the relevant concepts. A systematic literature review is performed to review and analyze the evolution of the overall concept of 'energy resilient building' and its application in the context of 'hot climate' and 'cold climate'. The Scopus database in Figure 1 shows the progress of the development of these key concepts from the year 2000 onward, as mentioned [19]. The x-axis in Figure 1 shows the number of publications during each year, and the y-axis shows the terms 'energy flexibility', 'energy resilient building', 'energy resilient building in hot climate', 'energy resilient building in cold climate', and 'energy resilient of building for heating system'. It can be observed that the energy flexibility concept has developed strongly since the year 2000 onward, and it is well understood. The interest and research on energy-resilient building have gained interest since 2010 and have been increasing in recent years, as shown in Figure 1. It is observed that there has been more focus on resilience in hot climatic conditions (appeared in 2011 onward). The energy-resilient building concept in cold climatic conditions is relatively new (appeared in 2016 onward), and considering the building's thermal mass with a heating system for resilience performance is still a novel concept. It is developing among the stakeholders such as scientific, academics, policy-makers and business communities with time, as shown in Figure 1. This shows that a rounded study is required that can define, develop a framework, model and validate the energy-resilient building in cold climatic conditions for the long term.

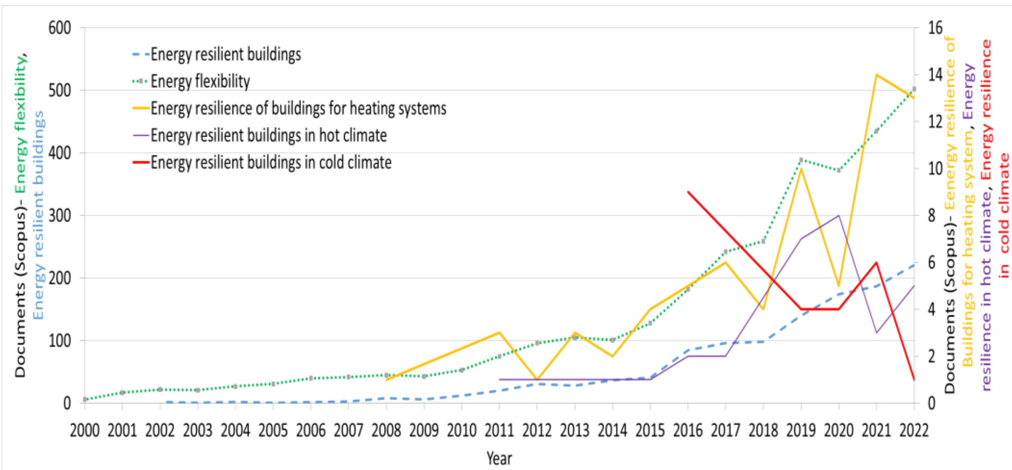

Figure 1. Appearance of the terms 'energy resilient building', 'energy flexibility', 'energy resilience building for heating system', 'energy resilient building in hot climate' and 'energy resilient building in cold climate' in the literature.

The main reason why the energy resilience of the building has not yet been studied in detail is because, like sustainability, it presents an abstract concept, and there are no clear definitions or guidelines; therefore, it can be difficult to plan for the energy resilience of the buildings. For example, some of the questions are: Against what must the building be resilient and thresholds? To what extent and duration should the building be resilient? As the building is a complex system, how can building and the energy flows within and outside the building boundary be resilient? How to define and build the capacity of the building to be resilient? To answer these questions and to plan for the energy-resilient building against disruptive events, a breakdown of the components, elements and their interaction that impact the performance of the building is required.

On the international level, research has been ongoing on the energy resilience of buildings at the urban scale [20] and limited research at the building level for mild climatic conditions [20–23], but very limited research has been carried out at the building level in cold conditions [16,21,24]. The few methods that are discussed in recent literatures [25–28] to improve the energy resilience in hot climatic conditions are utilizing the passive methods such as reducing the heat gains using shadings, better windows, envelope, ventilating the façade and green roof. Other methods discussed using evaporative cooling, thermal mass utilization, adsorption chillers, radiant cooling and heat sinks. The energy-resilient building concept has not been extensively explored for cold regions such as the Nordics. Methods to assess the impacts of extreme events and uncertainties on the design and performance of the residential building's envelope need to be thoroughly investigated in cold climatic conditions such as Finland. Moreover, methods to improve the energy resilience in cold climate also needs investigation. For example, in Finland, winter is extremely cold, and the outdoor air design temperature for the buildings' systems is −26 °C in Southern and −38 °C in Northern Finland [29]. The building has to be energy-resilient to maintain the habitability conditions during outage. Researchers have been focusing on 'habitability' in energy-resilient buildings [30], either for mild climate or for overheating conditions [21–23,31], and on short-term energy resilience. Therefore, similar discussion is required for cold climate.

The extreme cold waves with storms can cause energy crises due to increased energy demand, increased prices and power outage. It is possible that the likelihood of the events is relatively low, but the severity and damage can be very high on the habitable conditions for the occupants, especially in the case where elderly, disabled and ill people are the residents of the building [32,33]. A holistic study is needed that considers and presents the energy resilience concept for short- and long-term periods, especially in cold climatic conditions. Some earlier studies present the methods to estimate the short-term energy resilience performance of the buildings in warm temperatures [16,34]. The focus is mainly on the overheating conditions and their impact on the occupants [35], and a similar approach can be adopted for cold regions. This article investigates the research gap focusing on disruptive events (causing power outages) and their impact on the long-term energy resilience of buildings in cold regions. By bridging this gap, there is an enhanced understanding of the impact of disruptive events on the performance of the building performance in the long term. This article reviews and summarizes the scientific work that has been carried out earlier to define and analyze short-term energy-resilient buildings. The novelty of the article is to propose the novel concept, definition, indicators and framework that define long-term energy-resilient building in the context of the cold climate. Moreover, the thresholds are also suggested to estimate the performance of the energy-resilient buildings in cold regions. In addition, two case studies, i.e., an old and a new building in a Finnish climatic condition are presented for practice application of the proposed definition, framework and metrics indicators for energy-resilient building.

The paper structure is as follows: The energy resilience concept review and main components are mentioned in Sections 2 and 3. Section 4 provides the performance curve, metrics, minimum habitability and survivability thresholds for energy-resilient buildings in cold regions. Section 5 states the energy-resilient building definition and the main elements of the definition in cold regions. Section 6 provides the energy resilience framework and guidelines to estimate the energy resilience performance of the building. Section 7 provides the case studies on which the energy resilience definition, evaluation framework and metrics for the buildings are applied. Section 8 provides the discussion. Section 9 finally gives the conclusions.

2. Energy Resilience Concept: Literature Review

Energy resilience is a new topic that is under focus in present times due to challenges such as climate change, sustainability issues and energy crises. An energy-resilient building can respond to and sustain the changes and also recover towards stability after a disruptive event [36]. There is no specific definition for energy resilience in buildings as it depends on various factors (such as climate, socio-economic, policy and technical challenges) [37]. Energy resilience measures can be divided into short- and long-term measures. Short-term resilience focuses on the resilience performance of the building during a single disruptive event. The long-term resilience focuses on the long-term performance of the building, i.e., adaptation plan and learning from earlier disruptions (through rebound and feedback), so the building is more resilient in the next cycle of disruption compared to the earlier cycle of disruption. Table 1 presents the energy resilience definition found in the literature for the sector of built environments on cities and buildings' scales in different climate regions.

Table 1. Resilience definitions. Here '✓' represents that titled contexts are discussed in the definition, and '✗' represents that titled contexts are not discussed in the definition.

Definition	City Level	Building Level	Climate/Region Context	References
Ability to absorb, adapt and absorb to the disruptive event	✓	✗	Mild, hot	[38]
Ability to respond to the change and returning to stability	✓	✗	✗	[36]
Ability to minimize the interruption caused by the hazardous event	✗	✗	United States of America	[39]
Ability to plan for, recover from and adapt to adverse event over time	✓	✗	✗	[40]
Ability to tolerate disruptive event and continue to provide affordable service to the end user	✓	✓	United Kingdom	[41]
Ability to have a safe energy supply chain that can resist shocks and adapts	✓	✗	European	[42]
Ability to predict, absorb, adapt and recover fast from the disruptive event	✓	✗	United Kingdom	[43]
Ability to withstand disruptive event with high impact and low probability; recover fast after the event; learn to adapt and prevent impact	✓	✗	Mild, hot	[44]
Ability to maintain reliable operation during extreme event	✓	✗	United Kingdom	[45,46]
Ability to meet the desired performance levels during the disruptive event as it is in normal operation	✗	✓	United States, warm	[47]
Ability to recover to the normal and secure state after gradual decline under increasing stress and disruption	✓	✗	✗	[48]

The concept of energy-resilient buildings is derived from the 'reliability' of the electrical and heating/cooling power system, energy flexibility and stability, etc. [49]. The focus of the reliability concept is on the known threats against which the building or its system is designed; however, the resilience concept considers the extreme events that may not be known [37]. The difference between the two concepts is that reliability considers 'high probability low impact' cases; on the other hand, resilience considers 'low probability high impact' cases [50]. For instance, the electrical grid is a reliable network that provides electricity during the whole year without any interruption. Any interruption is usually handled through bypassing the outage network and using backup power plants [51].

Flexibility can be linked with resilience as flexibility considers the deviation from the normal; however, the difference between the two concepts is that flexibility considers a 'high probability low impact' scenario. Moreover, usually in flexibility the objective can be operational (energy) cost saving, whereas in resilience, habitability condition is the objective. For instance, the study carried out in Finland showed that by using the energy flexibility capability of varying the indoor room set-point temperature by 1.5 °C based on the price, the energy cost can be reduced [52]. The economical benefit is an important part of energy flexibility decisions. It is found that a ground source heat pump can save upto 15% of the operation cost [53]. By controlling the heating and cooling system of the building, 11% of the energy cost can be saved [54]. A resilient building can be built by designing and planning the building to be ready to address the 'unpredictability' nature of disruptive events and continuously changing environment. This is carried out by increasing the preparedness, absorption and recovery from different events for the short term while long-term resilience adaptation is also carried out.

The concept, definition and framework will provide the basis on which buildings will be designed and built to be resilient. This will support in defining a building's resilience level, whether resilient, less resilient or business as usual. Figure 2 shows the main queries needed to define the concept of energy-resilient building [16].

Figure 2. Fundamental questions related to the building resilience definition.

- Resilient for what: It is important to identify the definition of resilience, the stressor causing the disruptive events that impact the normal operation of the building [17,55].
- Resilient to what: The Intergovernmental Panel on Climate Change (IPCC) report shows that the climate-related extreme events such as forest fires, extreme temperature, storms, heavy rain, coastal erosion and earthquake have increased due to climate change [56,57]. Heat and cold waves can cause power failures due to overloading of the grid, etc., resulting in a decline in the building's energy performance [25,58]. In this study, the focus is on the power outage caused by climatic, political, economic and technical aspects, which ultimately impact the building's energy system, especially for heating-dominated regions.
- State of resilience performance: An important part of the energy resilience definition is to identify and observe what the building goes through or responds to during the disruption [27,37]. We propose a "multi-disruptive event curve" to show the repetitive energy resilience performance of the building under power outage. The phase and the indicators are discussed in detail in Section 4.
- Resilience assessment: The most important aspect of the resilience definition is the assessment. The assessment can be divided into two approaches: (i) qualitative and (ii) quantitative [26]. The qualitative approach is an assessment of the energy resilience in terms of its effect on the building's occupant's health, through observation without any numerical calculation [20,28]. The quantitative metric approach can be divided into two methods: an assessment method that is derived from the multi-disruptive event resilience curve [27,59–62], which considers different parameters that can impact an occupant's health, and another simple approach focuses on a single phase of the resilience curve during the disruptive event [63–65]. The following points are important to consider for the metric of energy resilience of a building:
    a. The resilience metric should be easy to understand and informative, so it can provide decision-makers with all the basic information needed to analyze the resilience performance of the building.
    b. The resilience metric should provide all needed information for the pre-disruption, during disruption and post-disruption phases.
    c. The resilience metric should provide resilience assessment for the building not only at the zone level but also at the whole-building level.
    d. The resilience metric should be sensitive so it can consider the severity, degree of shock, duration and impact of the disruptive event on the energy resilience of the building in the calculation.

Based on the above key questions and literature review, the energy-resilient building concept can be positioned and defined. The positioning of the energy-resilient building concept, framework for performance metric, minimum thresholds and definition for the energy-resilient building for the short and long terms in cold climate is illustrated in the following sections.

3. Energy-Resilient Building: Main Components

To build an energy-resilient building, it is important to specify the components of the building's energy system, the source of disruption as a stress creator, the impact and finally ways to manage the impact and reduce the stress. Figure 3 positions the concept of energy-resilient building, the main characteristics of impact and resilience attributes to build short-term and long-term resilience. All these components are critical to defining and understanding the behavior of the building under a power outage. Each component is explained in the following Sections 3.1–3.3.

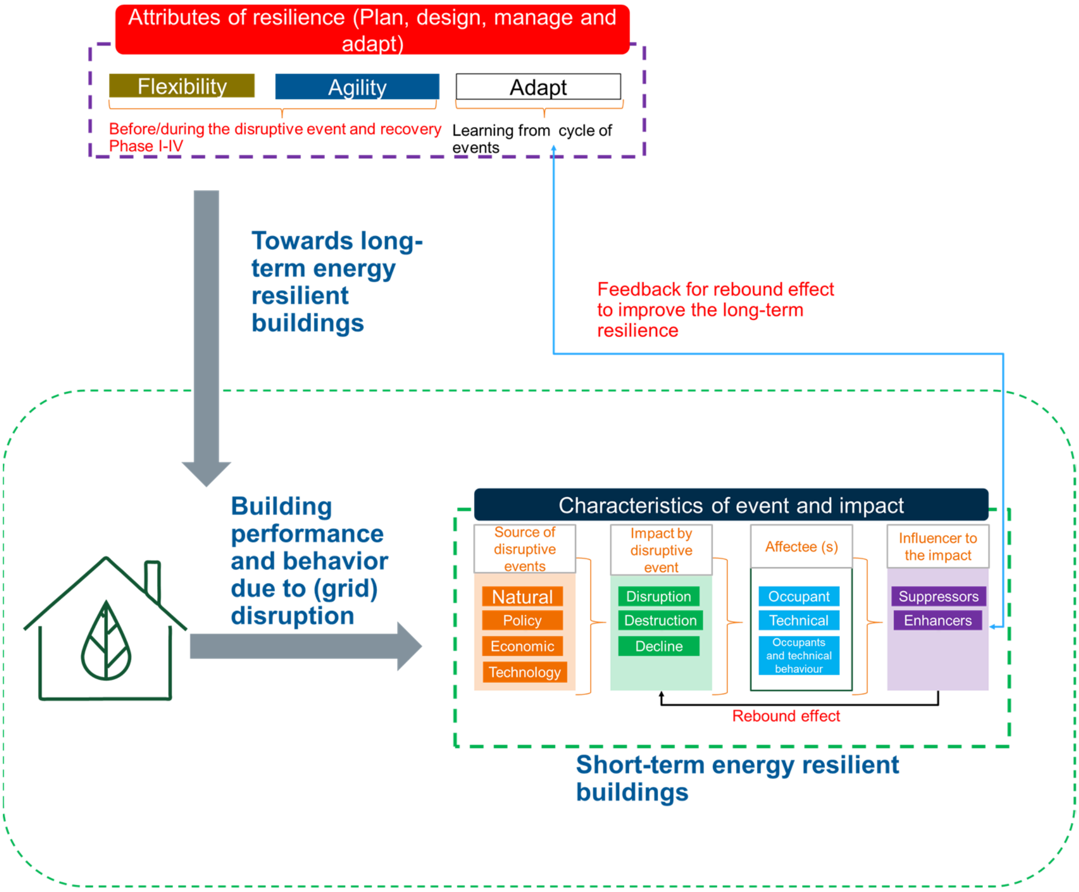

Figure 3. Positioning of the energy-resilient building concept framework, characteristics and attributes for the short term and long term.

3.1. Affectee(s)

Inside the building, there are physical components and social components. The physical components are the systems inside the building that support the living conditions and provide services, such as the technical systems, building envelopes and structures [66]. These physical components also interact outside the boundary such as with the grid and district heating/cooling network and domestic hot water, etc. The social elements can be human elements inside the building or the ones who come in/out of the building, which is an essential part of the building system. The social element can be further divided into individuals, groups of people and their activities. All these components, i.e., physical and social elements, interact with each other to create value (economic value) and well-being inside the building. These components of the buildings are important to be identified to understand the connections and their interaction. This will support in defining the energy-resilient building, framework, performance indicators and minimum thresholds and methods to manage both the physical and social components.

3.2. Main Source of the Disruptive Events (Stressors)

The resilience of the building has to be defined against the disruptors that can impact its performance and the occupants' comfort. To be energy-resilient and to measure the resilience performance of the building, the stressors and disturbers against which the building should be resilient have to be identified. It is important to mention that the building's physical structure may not be directly impacted by the discussed disruptive event; however, here the disruption event refers to the impact made by the grid, such as power shortage, power outage or brownout, that can directly impact the building's energy performance. In general, four different types of stressors can impact the performance of the building and the occupants' health and thermal comfort. These disruptive events are:

- Natural events: These are the events that are caused by various reasons such as meteorological (windstorms, snowstorms), hydrological (floods), geophysical (earthquake, volcano, landslide), climatological (heat wave, cold wave), and biological events (pandemic) [56,57].
- Policy: We have disruptors or stressors that involve humans directly and can be caused by their deliberate act. The biggest impact can be related to the policies and plans made by humans such as energy policies, financial plans and climate policies, etc. Other key human acts can be termed as acts of war, crime, terrorism, riots, etc. [13].
- Economics: Economic disruptions are caused by poverty, poor maintenance and deterioration of the housing and building, loss of business and poor investment in future plans or upgrades by the house owner, housing companies and property owners. The economic disruption can also be caused by external factors such as recessions that can cause power outages due to scarcity of resources and power.
- Technology: Technological disruption can be caused by the failure of the technical system. The technical systems are complex and interdependent so the chances of error are significant, causing disruption to the building performance [67]. The failure in the system can cause a cascade effect, and disruption may propagate through the system.

3.2.1. Impact by Disruptive Event

Disruptive events, disruptors and stressors can have a negative impact on the elements and components of the building. Some of the major impacts are as follows:

- Disruption: This can be defined as the loss of the performance of the product or system temporarily and its inability to function properly. This is a common issue such as power loss for a few hours or a day and can be called a disruption [68].
- Destruction: It can be called a situation where the loss is permanent to the whole system or part of the system. For instance, due to fire, or war, a part of the energy and grid infrastructure can be damaged permanently, resulting in loss of power. In this situation, one would need to plan alternative solutions.
- Decline: It is the reduction of the service or product life due to the use, end of lifecycle or obsolescence of the product or service. This situation can occur due to no or less maintenance of the product and service in the building. The decline can also happen due to the lack of resources and investment in the product and service to keep it relevant. For instance, a broken window, broken heating and ventilation system or non-functioning backup power system (batteries) can cause a decline in the service such as space heating in the building. Therefore, during a power outage, the resilience of the building will be lower.

3.2.2. Influencers to the Impact (Rebound and Feedback)

The occupants and technical products in the building can provide an influence on the impact of the disruptive event. For instance, if the occupants are aware and have experienced a power outage in the cold climate, they can be more equipped to sense the situation, prepare for, and respond to disruptive events. The impact will be lower with each successive event in the future called a rebound. Moreover, this building will be better prepared, and the impact will be less on this building compared to a building that is not prepared or is experiencing a disruptive event for the first time due to the learning and improvements. This is important for long-term resilience. In short-term resilience, the enhancers and suppressors can intervene, and the impact caused by the disruptive event can provide a feedback (learning) loop to either minimize or increase the impact of the disruptive event (in future cyclic events). The enhancers and suppressors can be defined as:

- Enhancers: It can be defined as a thing that can increase the impact, duration and severity of the disruptive event on the building. It can be called positive feedback as it increases the impact.

- Suppressors: It can be defined as a thing that can reduce the impact, duration and severity of the disruptive event on the building. It can be called negative feedback as it reduces the impact.

For example, the presence of well-insulated and energy-efficient buildings' envelope in cold climates and well-informed occupants in the buildings can act as a suppressor towards energy crises and power outages. For instance, the system and affectee(s) that have experienced a disruptive event are better prepared for the next disruptive event. On the other hand, if any of the learnings are missing, it may act as an enhancer to the disruptive event and can lead to higher impact and damage. Therefore, influencers are important both for the short- and long-term resilience of the building.

3.3. Attributes: Planning, Designing, Managing and Adaptation (for Long-Term Resilience)

After explaining the characteristics of the event, disruptive event, impact, enhancers, suppressors, the focus will be on the solution, performance indicators and calculation framework. To make buildings energy-resilient, the following key set of steps are important to be considered:

- Planning: Planning is important for energy resilience [69]. Planning here means to plan for a new component in the building envelope, control system and other devices that increase the resilience of the building. With planning, the capacity of resilience can be increased. The plans have to be flexible so they can keep up with the changes in the environment, conditions, challenges and new information. Urban planners and public bodies have realized that energy resilience planning has to be carried out with the end users of the buildings. However, there can be inflexibility from the stakeholders, end users or financial constraints that can limit the planning process for resilience.
- Designing: After planning, the designing process starts for resilience. There is feedback between the planning and designing phases. In the planning phase, as discussed, the flexibility of the plan is important so that new changes and new information can be incorporated into the design of the building.
- Managing and agility: It includes the decisions and actions that are taken during normal situations and in times of crises that impact the current and future states of the building. To be resilient, managing has to be carried out in an agile manner. The building and its system have to be managed to address the disruptive event. Moreover, it has to be agile to analyze the changes in the surroundings, use this information to assess the resilience and its impact by making proactive changes and give priority to certain loads of the building (such as heating, lights, etc.) to encounter the impact of the disruptive event on the building.
- Adaptability: In the adaptability phase, the building has to adapt to the environment and changes in the environment. When designing the building and its system, a focus has to be on adaptability that provides provision to redesign, remodel and modify during normal situations and under disruptive events. In this phase, the building system absorbs and learns from the disruptive event. This can be achieved through improved systems, tools, technology and prioritization. This provides a higher chance of effectively addressing a disruptive event cycle in the future. This will assist in reducing the impact, providing habitable conditions and then providing faster recovery after the disruptive event in the future. For instance, the management and adaptation actions that can be carried out to address and improve resilience are as follows:
    a. Building codes: The building codes can be improved and revised further so as not to only consider the energy efficiency aspect, but also consider the changing environment, energy crises issues and energy resilience-related challenges.
    b. Informed citizens and residents: The building, owners, housing companies, local authorities and government shall train the residents to be ready for energy crises.
    c. Warning signals: Early warning and detection systems in the building and energy systems can assist in reducing and managing the power outage.

d. Construct a special system for energy resilience: The building design, energy system, heating system and electrical system of the building can be pre-planned and installed according to the energy resilience requirements that can address the impact of power outages.

When considering the impact of disruptive events and the solutions for the resilience of the building [69], it is important to know the following two points:

1. Building structures are constantly changing. There can be a change in the envelope due to the maintenance or renovation. For example, buildings are renovated due to the upgraded building regulations, maintenance, etc., resulting in changes in the U-values. Similarly, the ventilation, heating and other electrical appliances may change with time due to maintenance. So, the resilience design of the building may change, and its parameters may change. Hence, it is important to keep track of the changed components and how they can impact resilience.
2. Early warning signals and detection of the disruptive event are important. This early detection signal can help in reducing the impact and assist in mitigating the outcome of the disruptive event. Therefore, it is essential to visualize the current state of the system for short-term resilience as discussed in the 'multi-disruptive event curve' in Section 4, to estimate the resilience performance of the building and plan using different disruptive events and behavior of the building in those events. In addition, the building should adapt for the future cycle of the disruptive event based on the learning of earlier disruptive events through rebound (feedback). The performance indicators and metrics are needed to provide a good understanding of the energy resilience level of the building for short-term and long-term resilience. All this can support reducing the impact of the disruptive event.

4. Multi-Disruptive Event Resilience Curve and Key Performance Indicators for Building Performance

To develop an energy resilience framework and indicators to calculate the performance of the building in the long term, the multi-disruptive event curve is developed. The curve can be created using simulation results or by measurements based on the indoor air temperature indicator as a measure of the energy resilience performance.

Figure 4 shows the multi-disruptive event curve and the typical behavior of the building under each disruptive event, such as power outages.

Different phases can be observed in the disruptive event curve of the building performance. Phase I is "before the disruptive event", phase II is "during the disruptive event", phase III is "after the disruptive event" and phase IV is "after the recovery". These phases define and visualize the short-term energy resilience of a building.

The behavior in phases I, II, III and IV depends on the following factors:

- Type, severity and duration of the disruptive event.
- Properties of the building's envelope (insulation, thermal mass capacity and air tightness).
- The energy system under consideration, such as the heating system, and energy generation and storage.

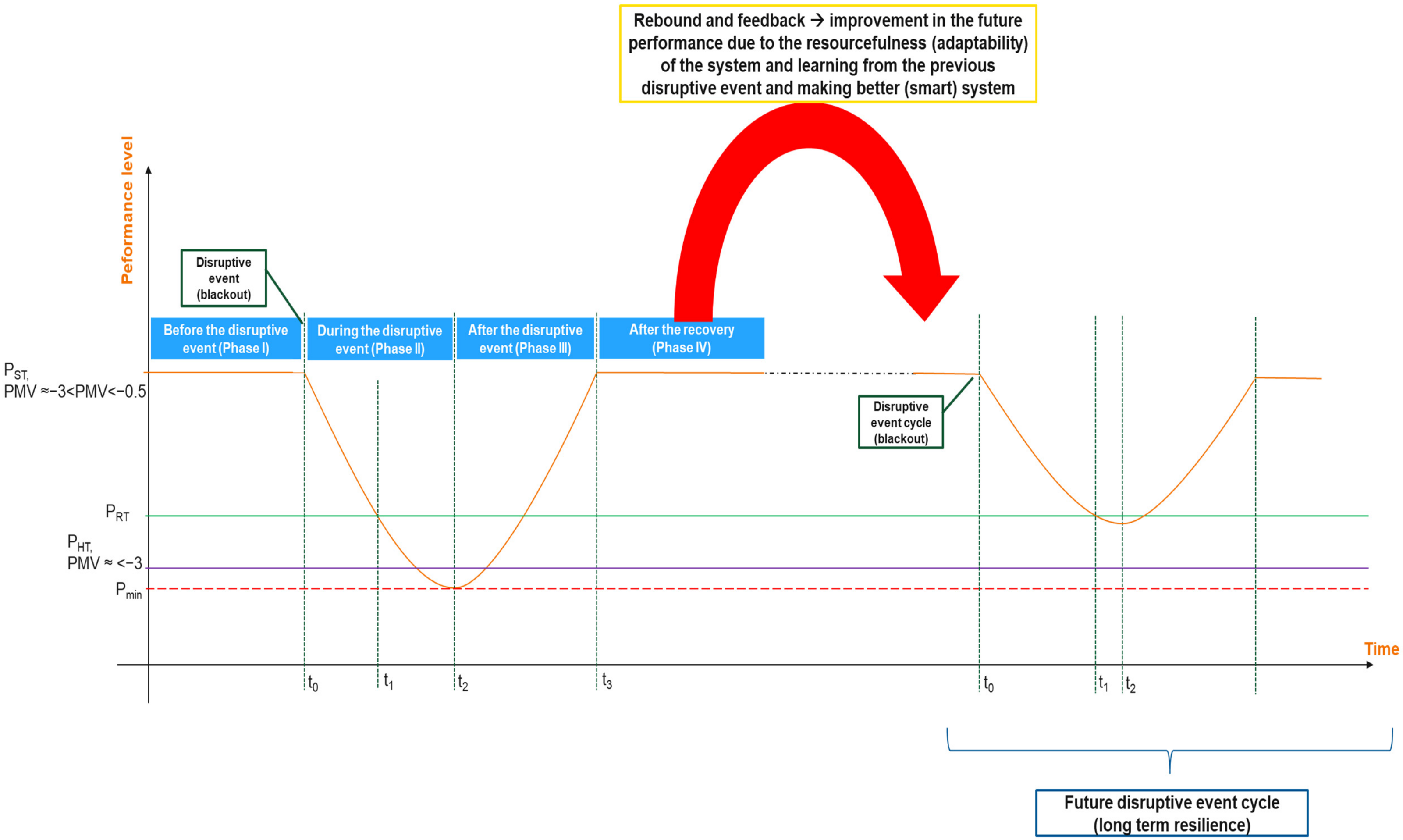

Figure 4. The multi-disruptive event resilience curve for long-term resilience.

Each phase for short-term and long-term resilience can be defined as:

- Phase I 'before the disruptive event' ($t < t_0$): Phase I is the state before the disruptive event. This stage can be called the preparation phase. In this stage, the building temperature, heating system and other energy systems operate at a normal state till a disruption such as a power outage occurs at t_0. At this phase, the predicted mean vote (PMV) for thermal comfort can be around $-3 < \text{PMV} < -0.5$, as recommended by ASHRAE 55 [70] for the heating season. It is important to note that PMV here represents suggested values and needs further analysis to define based on the climate and indoor conditions under disruptive events and level of dissatisfaction. The PMV for thermal comfort is based on the calculation given by Fanger [70] and used for normal conditions (without considering disruption). At this stage, the building can be in the state of performance for demand response, flexibility control or preparation for energy resilience, depending on the objective and signals.
- Phase II 'during the disruptive event' ($t_0 \leq t < t_2$): Phase II is the state during the disruptive event starting at t_0 and ending at t_2. This phase can be called the absorption and adaptation phase. P_{min} is the minimum performance reached in this phase. t_1 is the time when the performance reaches the robustness threshold (P_{RT}). During this period, the performance of the building reduces until it reaches the minimum level (P_{min}). At this phase, the predicted mean vote (PMV) for thermal comfort may reduce to -3 (which is acceptable) or a minimum PMV value that is less than -3 [70]. However, the building may remain habitable till it crosses the habitability limit P_{HT} (like indoor air temperature). The recommended limit for minimum PMV needs further discussion and analysis in power outage conditions. This is an important phase as the building will absorb the impact and then adapt to provide living conditions inside the building. To be resilient, the building system should be resourceful, so that it can use the local resources efficiently and prioritize the demand to control and mitigate the impact. The better the building envelope is (well insulated, heavy mass and airtight), the higher the resilience.
- Phase III 'after the disruptive event' ($t_2 \leq t < t_3$): Phase III is the state that initiates after the end of the disruptive event when the restoration starts. This phase ends when the building reaches its initial stage at the normal level of performance. This stage can be called the recovery phase. In this phase, the building is continuously recovering from the impact caused by the disruptive event.
- Phase IV 'after the recovery' ($t > t_3$): This is the final stage, and it starts when the building performance is fully recovered, and it operates at a normal level.

All the above phases are essential for short-term resilience. The novel part in the multi-disruptive event performance curve (Figure 4) is that it is extended with the rebound and feedback loop to introduce long-term resilience. For example, by learning from retrospective disruptive events, the building can be improved such as by improving the windows, using the onsite generation, storage (batteries) and smart controls (learning algorithms) to manage the building performance during a power outage.

This is done so that in a future cycle of disruptive events, the building will have the capability for adaptability and agility so it can learn from the previous disruptive events and improve, which is important for the long-term energy resilience of buildings. The new knowledge will help the building, energy system and occupants to adapt, use new tools and technologies, introduce new regulations and improve occupants' response. All these can help improve the energy resilience of the building by increasing its robustness, management and prioritization to mitigate the impact. With each disruptive event, the building envelope, energy system and end-user behavior are improved. To be effective, the improvement should be carried out with an integrated smarter system. The smartness is increased at the system level, such as integrating a warning system, control system to manage loads, additional storage, etc., and at the social level by informing the occupant for certain actions during the disruptive event, such as reducing the indoor set-point temperature, closing the windows (to reduce the losses), switching off non-essential loads, etc. By improving the system, the building becomes more resilient, so the impact of a future disruptive event is less severe compared to the earlier event. In Figure 4, the curve on the left can be compared with the curve on the right, i.e., the future performance curve, to analyze long-term resilience. The curve on the right should be better compared to the curve on the left in three aspects. Firstly, the decay of the indoor temperature during Phase II should be slower. Secondly, P_{min}, the minimum failure point in Phase II, should be higher. Thirdly, in Phase III, the recovery time shall be faster. The analysis of the consecutive disruptive cycle, which is before the rebound and after the rebound (feedback and learning), has to be studied to analyze and recommend improvement so the system and the end user act as a suppressor, as discussed in Section 3.

Figure 4 can be used to derive a framework for the performance indicator to estimate the energy resilience level of the building. To visualize, assess and measure the state of the performance of the energy resilience of the building, the first thing is to identify the severity and duration of the disruptive event. It is important to define, classify and quantify the impact of different disruptive events on the indoor environment of the building. To quantify the impact, the concept of the degree of disruption (DoD) is introduced in this article. A similar concept is discussed in [71]. Equation (1) defines the degree of disruption (DoD):

$$\text{DoD} = \frac{Parameter_{disruption} - Parameter_{reference}}{Parameter_{reference}} \times \frac{Time_{disruption}}{Time_{reference}} \tag{1}$$

Equation (1) quantifies the disruptive event severity and its impact on the performance of the building. Severity is the increase or decrease in the calculated parameter during the disruptive event ($Parameter_{disruption}$), compared to the reference parameter value in the normal situation ($Parameter_{reference}$). The parameter that is estimated depends on the indicators that are relevant for the energy-resilient building such as indoor temperature, energy demand/consumption, electrical load, end-user discomfort, etc. The time duration is the ratio of the $Time_{disruption}$ $t_2 - t_0$ (duration of the disruptive event) and $Time_{reference}$ (i.e., the total duration of the observation or total designed operation time of the system). Hence, the DoD combines the severity and the duration of the disruptive event so that the higher the DoD, the higher the impact of the disruptive event.

Based on the performance levels and using a similar approach to define performance indicators in the field of power resilience [72], the energy-resilient building framework and performance indicators are defined in the article. In Figure 4, different performance levels can be observed. These levels are used to define the resilience performance metrics of the building.

- P_{ST}: It is the target set point for the indicator (such as indoor set-point temperature). This is the set point for the normal operation of the building.
- P_{RT}: It is the robustness threshold of the building. Any performance level above this value can be considered robust. Any performance below this point is not robust. In Figure 4, t_1 is the time point below which the performance of the building is not robust. The robustness threshold is discussed in Section *Habitability Threshold*.
- P_{HT}: It is the habitability or survivability threshold for the building's occupant. If the building's performance goes below this level, it then means that the building has failed to provide minimum thermal living conditions for the building's occupants. However, if the building recovers before reaching this point, then the building can be considered resilient. Below this point, the building is not resilient. The minimum threshold for habitability is discussed in Section *Habitability Threshold*.
- P_{min}: It is the minimum performance level the building reaches due to the disruptive event.

Table 2 shows the key indicators and metric calculations that can be used to define the energy resilience performance level of buildings.

Table 2. Energy resilience metrics during the phases.

Metric	Name	Definition	Equation
DoR	Duration of robustness	It defines the duration the building can maintain the defined resilience performance after facing the disruptive event (power outage).	$t_1 - t_0$
SoC	Speed of collapse	It defines how quickly the performance of the building deteriorates from the set point. The lower the speed, the better the performance of the building in absorbing the impact.	$(P_{ST} - P_{RT}) + (P_{RT} - P_{min})/(t_2 - t_0)$
IoE	Impact of event	It provides the impact of the disruptive event and the minimum performance of the building that will be experienced during the disruptive event. The smaller the value, the better the building is in terms of resilience performance.	$(P_{ST} - P_{RT}) + (P_{RT} - P_{min})$
SoR	Speed of recovery	It defines the speed at which the building can recover after the disruptive event and reaches the target set point.	$(P_{ST} - P_{RT}) + (P_{RT} - P_{min})/(t_3 - t_2)$

Section *Habitability Threshold* describes how the minimum thresholds in cold regions are defined and explains the habitable threshold beyond which the physical and mental health of humans may suffer.

Habitability Threshold

The main objective of the energy-resilient building is to maintain a minimum performance level of habitability and survivability conditions as long as it is needed and technically possible. Another objective of the energy-resilient building is to minimize the physical damage to the building assets. In a normal state, a building and its controls are operated at normal standard states that are designed according to regulations in force, best practices or local guidance, where the aim is to provide comfort and well-being to the occupants. However, under the stress caused by a disruptive event, it is no longer possible to operate at the standard defined state and set points. In such conditions, efforts are made to maintain a minimum indoor environment to prevent discomfort during the progress of the disruptive event and to protect the well-being of the occupants. Accordingly, there will be a drop in the indoor temperature in cold climates and reduction in the ventilation rate, humidity level, lighting level, electricity consumption, etc. These aspects above are important because they have an impact on the thresholds of the performance, well-being and physiological conditions of the occupants of the building. The physiological response depends on the magnitude and rate of change in the indoor temperature of the building. The rate of change in the indoor environment depends on the mass and insulation level of the building's envelope, which is especially important in cold climates. Moreover, the physiological conditions of a human depend on the personal insulation (clothes) against which a human is protected against any change in the indoor environment. A normal operation of physiology occurs when the human's core body temperature is 37 °C. When the building's indoor environment changes, it can impact the core body temperature. If the core body temperature does not respond effectively to a large change in the indoor environment, then the normal function of the human body can be compromised [33].

The physiological/psychological signs include the following:

- Discomfort.

- Numbness.
- Shiver.
- Skin vasoconstriction.
- Cold becomes a distraction.
- Hyperthermia.
- Muscle stiffness.
- Cognitive changes (confusion, apathy, loss of attention, reduced memory capacity, etc.).
- Loss of sensory information (blurred vision).
- Cardiovascular effects.
- Loss of consciousness.

In general, in cold climates, clothes can create insulation that can protect humans from cold conditions. With an insulation layer on the body, a human can survive at 5 °C when the clothing is able to create a microenvironment that is equivalent to a mild temperature of 22 °C [73]. However, even with this clothing, the cold conditions for long periods can affect humans as discussed above. The discomfort, distraction and disability to perform in the cold environment increase significantly when the temperature decreases from 20 °C to 10 °C [73]. In these conditions, humans spend time addressing the discomfort and can lose focus on other tasks. Similarly, people with different backgrounds, cultures, experiences, genders and ages are affected differently when exposed to a long cold environment. All these connections and their impact on the human physiological and psychological states are complex and need deeper analysis.

In the event of a disruptive event of power outage, an energy-resilient building has to be designed so that it can meet the minimum habitable conditions for the occupant, provide survivable conditions and protect building assets and materials. In case of a power outage, the electrical supply to the heating system, air handling unit, ventilation, water pumping and the electrical loads is not available, and this will cause the decay of the indoor room temperature and other functions. The rate at which the temperature decays depends on many factors such as the building's envelope structure properties, outdoor temperature, type of the heating system, internal load, backup system, etc. The performance of the building under power outage and temperature decay needs to be modeled for various cases to analyze the behavior of the building and its energy resilience potential [74] against certain minimum thresholds. Table 3 shows the minimum threshold and habitable conditions for the building in cold regions from the studies [29,33,70,75–77]. In addition to the minimum temperature levels, the PMV level is also provided for thermal comfort [70]. It is important to note that the PMV values are given as an initial example from the literature and require further analysis based on the climate and indoor conditions of the building in a power outage. It is also important that either one of the minimum threshold levels, that is temperature or PMV level, could be satisfied for the occupant habitable conditions during power outages so that the building can be called energy-resilient. For the electrical load, it can be based on the local requirement; for instance, minimum requirements for refrigeration, telecommunication and lighting demands in the residential building are important to survive. This can be used as a reference under a power loss. Both the habitability condition and load requirements are needed to meet the habitability and survivability thresholds for the end user in cold climates.

Table 3. Thermal conditions for buildings located in cold climate in resilience operation according to the literature and best practices.

Type of Requirement	Minimum Robustness Threshold (P_{RT})	Minimum Habitable Temperature (P_{HT}) or Adaptive Comfort Temperature Level	Minimum Robustness PMV (Cold)	Minimum Habitable PMV (Cold)
Occupant comfort	18 °C	16 °C	$-3 < \text{PMV} < -0.5$	<-3
Building assets protection	Minimum temperature 4.4 °C	Humidity level 80%		

In addition to the specified temperatures, another approach can be adaptive comfort temperature level (ACTL). This has been mainly discussed in the context of overheating [78]. For example, it has been used in Dutch building [79,80] and incorporated in the Dutch standard ISSO Publication 74 [81]. This concept is developed for an environment that is naturally ventilated, and the occupants have the freedom to choose the clothes, window opening, ventilation, etc. The term adaptive is suitable for office-like setups or living rooms; however, limits have to be applied for adaptability, otherwise the thermal environment can lead to very high or very low values for temperature [82]. It is found that people feel warmer in their homes compared to the office even with the same indoor climate, doing the same activities and wearing the same clothing [82]. This is due to the presence of furniture, carpets, and wallpaper as possible reasons. For the residential building, Peeters de Dear et al. [83] developed an adaptive temperature level for overheating. A similar approach can be used to define an adaptive comfort temperate level (ACTL) for cold climates based on the study [83] in Equation (2). The minimum threshold defined in Table 3 can be replaced with the ACTL after performing further analysis and user acceptance. Here, it is defined as an initial threshold for further discussion, and this can be called minimum adaptive habitable temperature (MAHT).

$$\text{MAHT} = \text{Min}\,\{16\ ^\circ\text{C},\ T_n + \omega\alpha\} \quad (2)$$

For $T_{ref} < 0\ ^\circ\text{C}$	$T_n = 16\ ^\circ\text{C}$
For $0\ ^\circ\text{C} \le T_{ref} < 12.6\ ^\circ\text{C}$	$T_n = (0.23T_{ref} + 16)\ ^\circ\text{C}$
For dissatisfaction = 10%	$\omega = 5\ ^\circ\text{C}$
	$\alpha = 0.7$

where T_n is the neutral temperature (World Health Organization value of 16 °C will be accepted as a minimum of the neutral temperature for winter conditions), ω is the amplitude of the thermal comfort band when the dissatisfaction is 10%, α is constant and T_{ref} is the average daily temperature.

Depending on the climate, moisture, building surface material and humidity, there is a high chance of developing mold if the indoor environment in cold regions is not properly maintained. During a disruptive event of a power outage, the indoor room temperature drops, which causes mold on the building surface. Therefore, minimum temperature and humidity conditions must be maintained to protect the building assets (Table 3). Another issue is the piping and bursting of the pipe due to the cold climate. There is a risk of freezing of the water in the pipe, which can cause a rupture in the pipe and water damage in the building. Therefore, it is important to avoid sub-zero temperatures in the pipe, or drain the water from the system, providing pressure relief value in the network and air expansion.

5. Energy-Resilient Building Definition and Elements

The definition of energy-resilient building is developed as the first step based on the literature review and concepts discussed above. This definition is presented as an example after the discussion with the authors of [16]. The authors are experts in the field of building simulation, energy flexibility, energy resilience and renewable energy systems. Our basic definition of an energy-resilient building is:

An energy-resilient building is a building that can maintain the indoor temperature within the habitability thresholds for the building's occupant and also provide survivability conditions by maintaining a low level of electrical power for essential services (such as ventilation, refrigerator, communication and other basic loads) during a disruptive event of a power outage. The aim is to keep the building in a condition that does not risk the health and life of the building's occupants or damage the building's structure. Such a building is expected to be energy-efficient to conserve heat and energy. An additional' merit of the building is to improve its long-term resilience for future disruptive event cycles by smart design learned from rebound effects from past events.

The elements that are included in the definitions are:

- Habitability is the ability of a building to maintain the indoor temperature within defined habitable temperature thresholds during a disruptive event of power supply loss. Habitability is then about thermal resilience characteristics. The indoor temperature inside the building has to be defined, e.g., whether it is the indoor air temperature, the operative temperature or any other measure of temperature [84]. The minimum levels are discussed in Table 3.
- We here differentiate between two related concepts in habitability: Passive Habitability and Active Habitability. In Passive Habitability, the building makes use of its envelope insulation and air tightness against the outdoor environment for heat conservation, its mass thermal capacity for heat storage and the natural source of solar radiation for heat gain. In Active Habitability, active components of energy generation and storage in the building (e.g., PV, fuel-driven electric generator, electric battery, hot water storage tank) can be added to extend the habitability duration.
- On the other hand, survivability is the ability of a building and its active components of energy generation and storage to maintain a minimum operational condition during a disruptive event of power supply loss. This minimum operating condition maintains the indoor temperature within the habitability thresholds, but it also maintains a minimum energy supply for basic services, e.g., minimum levels of lighting, ventilation, appliances, sewage and domestic hot water supply [85]. Depending on the assumed duration of the disruptive event, these buildings will be designed to survive and provide the essential services to end users for durations of 3, 5 or 7 days.
- When possible, the minimum adaptive habitable temperature (MAHT) can be used to define the threshold levels and present a similar table as Table 3.

6. Energy Resilience Framework

A systematic approach is presented to assess a building's energy resilience level in cold regions. These steps can classify buildings according to their energy resilience levels. It is first required to define the reference conditions that will establish the basis of comparison of the resilience characteristics. These reference conditions should, as a minimum, specify:

- The selected zone.
- The weather data of the disruptive event (typical weather TMY, past real weather, future weather, extreme weather, synthetic weather, etc.).
- The duration of the power outage.
- The normal operating set-point temperatures in the building.
- The habitability temperature thresholds.
- The minimum level of power required for survivability per each category of consumption.
- The scenarios of the power restoration.
- It is then that the building's resilience level is calculated.

The above can be conducted for another building to compare and classify the buildings based on their resilience levels.

Figure 5 shows the main steps of a suggested generic framework to assess the energy resilience of a building. The feedback from the short-term performance is utilized for the improvement and adaptability of the long-term resilience by learning in a smart system. As it is a generic framework, the steps can be adopted based on each case.

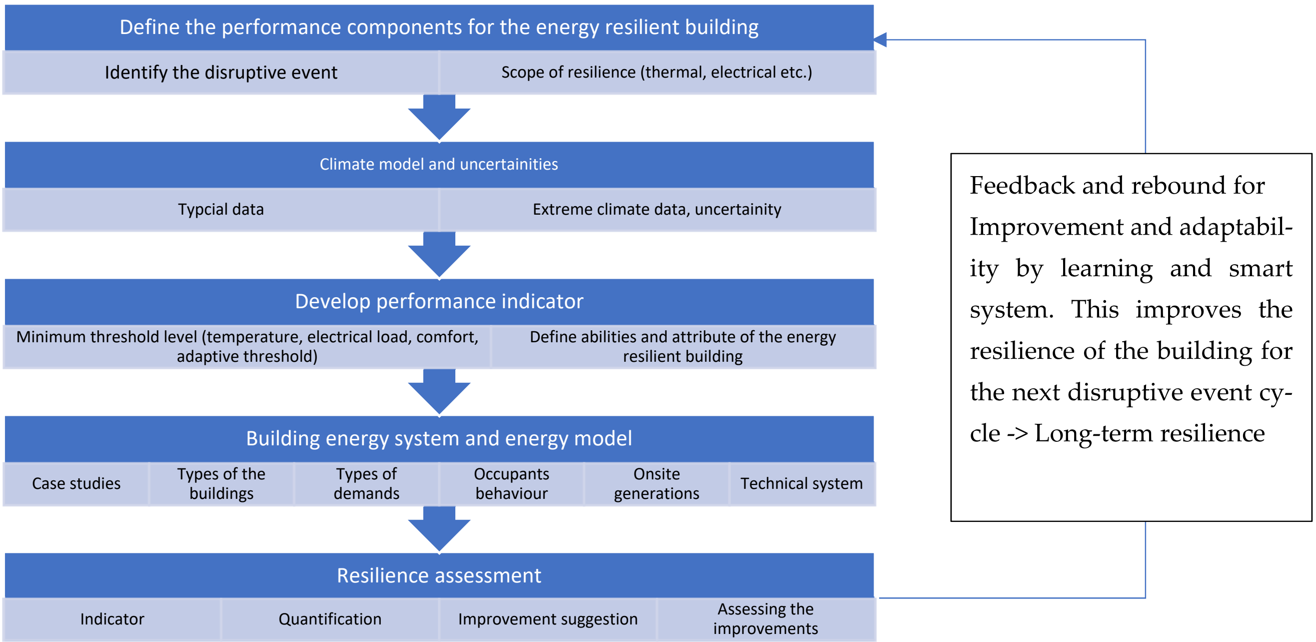

Figure 5. A general framework to define and assess the energy-resilient building for short- and long-term resilience.

7. Case Studies: Energy-Resilient Buildings Concept Application

Two case studies of the single-family old and new residential houses are presented as an example to utilize the method, indicators and thresholds to represent energy resilience performance in Southern Finland. The old building was constructed during the 1970s, and the new building was constructed during the 2020s. It is assumed that the buildings have a floor area of 140 m^2. Table 4 shows the design values of the two types of buildings used in the study. The study focuses on the heating demand. It is assumed that the building is heated using a radiator and direct electricity (electric heater) to produce heat. The heater capacity is designed such that it is able to maintain the indoor temperature at 21.5 ± 0.5 °C in the building during winters.

Table 4. Old and new building properties in Finland [29,86].

Building Type	Walls (W/m^2 K)	Roof (W/m^2 K)	Floor (W/m^2 K)	Windows (W/m^2 K)
Old building	0.5	0.5	0.27	0.38
New building	0.17	0.09	1	0.16

The input that follows the energy resilience evaluation framework as described in Section 6 are:

- The typical reference year weather data are used for yearly simulations [87].
- Yearly simulation is carried out, and the duration of assessment is between 1830 h and 1900 h for the old and new buildings.
- It is assumed that the power outage starts from 1854 h and the duration is 30 h.
- The normal indoor set-point temperature is 21.5 °C.
- The robustness threshold is 18 °C, and the habitability threshold is 16 °C.
- The power is available from 1884 h onwards.

It is assumed the power outage occurs between 1830 h and 1900 h for the old and new buildings cases when the ambient temperature is below 0 °C (around −10 °C). It is assumed that the power outage occurs at 1854 h and the duration is 30 h (no energy for heating is available). Figure 6 shows the indoor air temperature behavior during the power outage. In Figure 6, all four phases of the performance curve are shown, which is similar in pattern (as in Figure 4). In Figure 6, Phase I is before the outage (normal operation), Phase II is the point when outage occurs, Phase III is the point when recovery starts after the availability of grid and Phase IV is the point when indoor air temperature reaches the target set point.

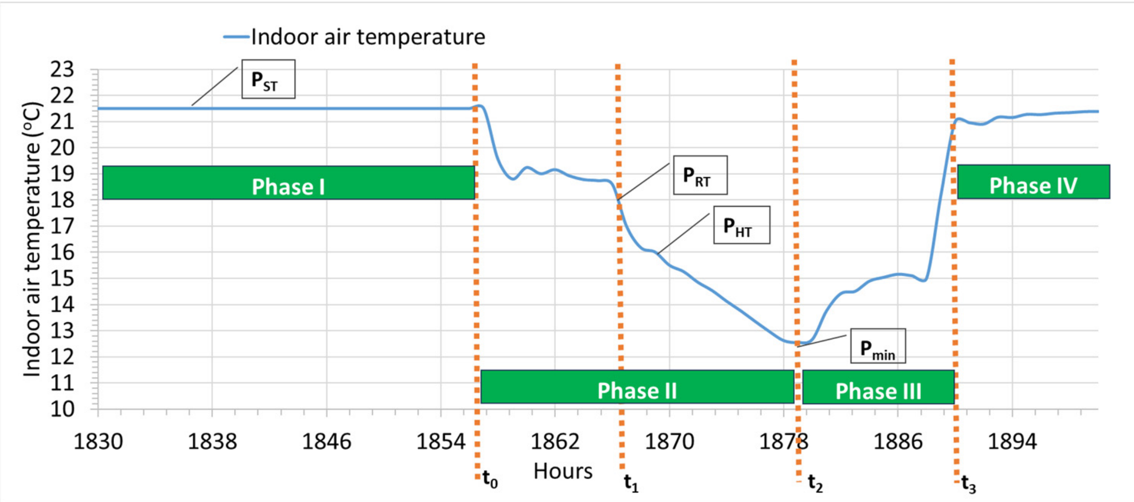

Figure 6. Energy resilience performance curve, terminology, thresholds and metrics indicator for a simulated old building in Finland.

It can be observed in Figure 6 (blue line) that the indoor air temperature drops from P_{ST} = 21.5 °C (time marked 't_0') to P_{RT} = 18 °C (the robustness threshold) in 11 h (time marked 't_1'). Hence, the robustness period is 11 h for the old building. As the power outage continues, the temperature reaches the habitability threshold of P_{HT} or MAHT = 16 °C in 5 h after crossing the robustness threshold. The MAHT is also assumed to be 16 °C, as the outdoor temperature is below 0 °C. The minimum temperature (P_{min}) is 12.54 °C (time marked 't_2'). After the availability of power, the indoor temperature reached 21.5 °C in 1891 h (t_3).

Similar hours (1830 h to 1900 h) and conditions are selected for testing the impact of power outage on the energy resilience performance of the new building, as conducted with the old building. In Figure 7, all four phases are shown, which represents Figure 4. In Figure 7, it can be found that indoor air temperature drops from P_{ST} = 21.5 °C (time marked 't_0') to P_{RT} = 18 °C (robustness threshold) in 26 h (time marked 't_1'). Therefore, the robustness period is longer for the new building compared to the old building (Figure 6). The building remains above the P_{HT} or MAHT of 16 °C. This shows that the new building remains habitable. The minimum temperature (P_{min}) is 17.5 °C (time marked 't_2'). After the availability of power, the indoor temperature reached 21.5 °C in 1886 h (t_3).

The indicators and metrics as shown in Tables 2 and 3 are applied in the above two case studies. The key findings are shown in Table 5. Based on the definition, metrics and indicator framework described in Sections 4–6, the case studies' results are shown in Table 5. It is observed that the new building has better energy resilience performance compared to the old building. Similar methods can be used for other buildings, climate and locations.

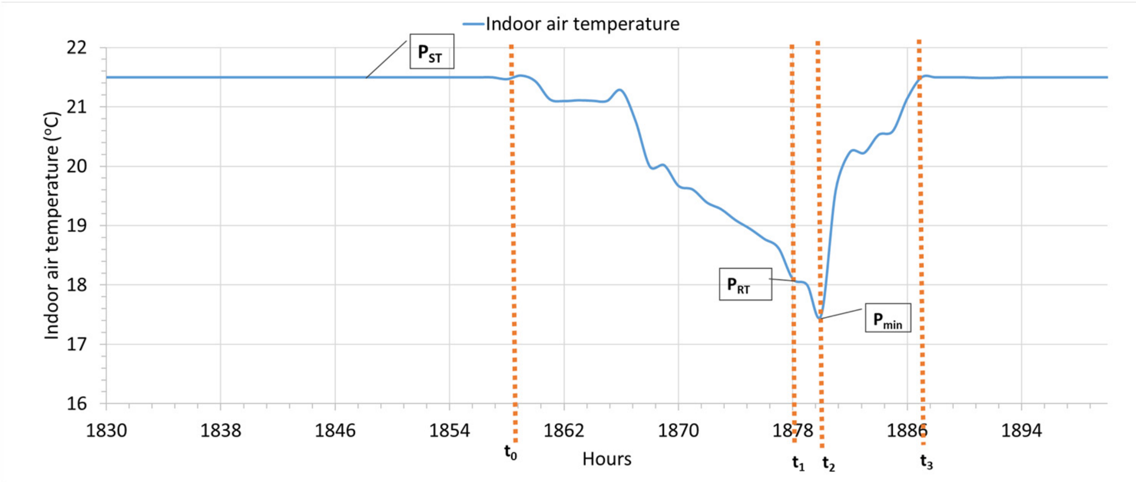

Figure 7. Energy resilience performance curve, terminology, thresholds and metrics indicator for a simulated new building in Finland.

Table 5. Energy resilience metrics and performance analysis for the case studies, i.e., old and new buildings in Finland.

Metrics	Old Building	New Building
P_{RT}	18 °C	18 °C
P_{HT} or MAHT	16 °C	16 °C
P_{min}	12.54 °C	17.5 °C (higher is better)
Degree of disruption (DoD)	0.300	0.138 (lower is better)
Speed of collapse (SoC)	3.75 °C/h	3.2 °C/h (lower is better)
IoE	8.9 °C	4 °C (lower is better)
SoR	0.64 °C/h	0.80 °C/h (higher is better)

Based on the above-proposed energy resilience definition framework and metrics, it can be summarized that the disruption caused by the power outage resulted in a decline in the thermal energy services. This affected the indoor air temperature and the occupant's habitability. The metrics provided a numerical comparison between the behavior in the two cases studies. By learning from the power outage disruptive event, the building design and envelope components can be improved to cope with any long-term resilience event. For instance, the building envelope and windows can be improved. Similarly, integrating energy systems such as photovoltaic and batteries can support in further improving the resilience. This also requires smart controls to optimize the load and available onsite generation. The end user can plan these improvements in the building by renovating the building and act as a suppressor to reduce the disruption impact on the building. They can also lend support by acting in certain ways during a power outage, for example, in reducing the heat losses during the outage by closing the windows, closing doors, prioritize energy requirements and reducing the ventilation rates, etc.

8. Discussion

The building's energy performance and resilience can be increased through various passive and active methods that are briefly discussed and requires further studies depending on the location. The building energy performance and thermal resilience can be increased through architectural elements and passive design [35]. For instance, glazing is an important element of the building that can impact the performance. There can be static or dynamic glazing elements. Fixed glazing, with its predetermined optical and thermal qualities, lacks the capacity to adapt to changing environmental conditions, whereas dynamic glazing technologies, like optically switchable (or smart) windows, can alter their properties [35] and support in improving the consumption and energy resilience.

Another important element can be the fixed and movable shading of the building that can support in improving or reducing the heat gains [34]. Some other new technologies that are discussed in the literature which can support in improving the performance and resilience of the buildings are ventilated or natural ventilated façade [34], color paints [34] and green roofing/façade [88]. In additions, the building location, neighborhood and surrounding buildings, the façade orientation and the building use are some of the elements that can impact the performance, and this requires analysis [35].

The energy and resilience performance of the building is highly impacted by insulation of the envelope (walls, roof and floor). Retrofitting the old buildings and using insulation in new buildings improves the efficiency and energy performance [89]; this also improves the resilience. Some of the common insulation materials are fiberglass, mineral wool, rock wool, plastic fibers, natural fibers, foam board and polyurethane, etc. [90]. The ventilation and efficient heat recovery system that is part of the building can also support in reducing the losses and improving the energy resilience of the building. By varying the ventilation rates, the heat and cooling requirements inside the building change. Hence, during the power outage, the ventilation rates can be altered compared to the normal operation, in order to reduce the losses through ventilation.

The air tightness is important as it also impacts the resilience and energy performance. This can be done by renovating the old windows and doors. With lower U-value of the windows and doors, the heat loss of the building reduces. Some of the ways to further improve the airtightness is using airtight seals around the windows and doors that draught-proof the openings and using double-glazing windows. Using solid continuous ribbon and rubber seals around windows and doors can improve energy performance. The piping holes, cable holes, chimneys, loft hatches and trap doors can be air-tightened for higher performance [91,92]. All these steps reduce the losses and improve the performance.

Adding the onsite solar photovoltaic, solar thermal, wind turbines with heat pumps can support in improving the performance by reducing the impact of power outage, as these systems can provide energy during blackouts. Another option is to have a backup generator (diesel-, petrol- or gas-based). However, this may cause emissions pollution so more sustainable solutions are recommended [89,93]. To utilize such solutions in the future, the buildings and districts need to be developed, redesigned, remodeled and modified so they can allow integration of onsite renewables and storage in the building structure [94,95]. Policy support is also needed. These technologies can provide energy flexibility and resilience to the buildings during normal situations and under disruptive events.

The energy storage also impacts the resilience performance. At the building level, electric battery, hot water storage, boreholes [85] and phase change materials can be added to extend the habitability duration and resilience [96]. This also requires planning, costing, and sizing for optimal and feasible solutions. For higher resilience performance during the power outage, the typical electrical heaters can be replaced with effective systems such as heat pumps, demand-based water heaters, radiant heaters and phase change material integrated walls. The waste heat recovery from district heating network and data centers can be used to improve performance of the buildings and reduce the energy cost if this is available nearby [97]. This can also provide backup heating during power outages. This also requires further studies for optimal design and integration [52].

Smart controls and monitoring systems are important as they can provide savings in terms of energy costs, improve the use of onsite generation sources, increase flexibility, charge/discharge the storage, control grid interaction, utilize the backup systems and improve the resilience. Some of the projects such as EXCESS, SPARCS, MatchUp are developing these controls and monitoring methods for demo buildings in Europe [98,99] for flexibility and cost reduction, using pricing signals. These controls methods can be further developed that can provide resilience during power outages by controlling the onsite generation, storage and demand prioritization for optimal performance during disruptive event operations.

Finally, the end-user and occupant behavior also impact the energy consumption profile and the resilience performance [100]. For long-term resilience, if the occupants are aware and have experienced a power outage, they can be more equipped to sense the situation, prepare for, and respond to disruptive events. This can be done by co-creating, engaging, and through the learning process of the end users. Such buildings and end users are better prepared to face the challenge, which can lower the impact of the disruptive events. For instance, teaching the occupants about using appliances or prioritizing loads during certain times of the day can help in reducing the energy cost, lower the peak demand and improve the resilience of the system.

9. Conclusions

Transition towards sustainable cities and districts is needed to mitigate the impact of climate change. To build sustainable cities and buildings, it is important to consider the future challenges and disruptive events by having energy-resilient buildings. If the sustainable and resilient transition is not considered in the future urban plan, it could then cause great human loss and economic loss. If considered, then such a society can offer higher flexibility, reliability, resistance, robustness and recovery toward a normal state.

Based on the literature review, it is found that the energy resilience building concept has not been extensively explored for cold regions such as the Nordics. The concept and definition are still at an early stage and require further development and clarification for the cold conditions. The similarities between different concepts have to be identified. Moreover, research has been focused on the warm climate, with overheating conditions and short-term resilience. This article investigates the research gap focusing on disruptive events (causing power outages) and their impact on the long-term energy resilience of buildings in cold regions. In this study, a basic definition of an energy-resilient building is introduced as, an 'Energy resilient building' is a building that can maintain the indoor temperature within the habitability thresholds for the building's occupant, and also provide survivability conditions by maintaining a low level of electrical power for essential services (such as ventilation, refrigerator, communication and other basic loads) during a disruptive event of a power outage. The aim is to keep the building in a condition that does not risk the health and life of the building's occupants or damage the building's structure. Such a building is expected to be energy-efficient to conserve heat and energy. An additional merit of the building is to improve its long-term resilience for future disruptive event cycles by smart design learned from rebound effects from past events.

The paper presents a framework to design, estimate and classify the energy resilience performance of buildings, especially in cold regions. It consists of the following steps.

1. Define the performance components, scope, building type.
2. Define the type and extent of the disruptive event.
3. Define the weather/climate model.
4. Define the performance indicator that needs to be evaluated.
5. Define the thresholds for the indicator.
6. Conduct the simulation, monitoring of the building performance.
7. Quantify the indicator values and compare them with the thresholds.
8. Classify the level of resilience.
9. Provide improvement suggestions for long-term resilience.

The framework can be adapted based on the case and the local requirements. Moreover, the minimum adaptive habitable temperature (MAHT) can be used, when possible, to define the minimum thresholds, based on the local conditions. The PMV model, which is used in real conditions for comfort thresholds, can be studied for possible development for use in power outage situations in cold regions. The definition and framework provided in the article can act as the base for future studies and also for the improvement of the building regulations.

Two case studies of an old and a new building in the Finnish climatic conditions are presented as application cases in which the proposed energy resilience framework is considered. The main findings of the energy resilience performance of the two studied buildings are summarized as follows:

- For the old building, the P_{RT} threshold and robustness period is 11 h. The P_{HT} threshold and duration is 5 h. Moreover, the IoE is 8.9 °C, resulting in a large impact of the power outage compared to the new building in a similar climate. The P_{min} is 12.54 °C and DoD is 0.300, which is higher compared to the new building.
- For the new building, the P_{RT} is 26 h. The building remains above the PHT thresholds, meaning the building remains habitable and resilient for 30 h. The IoE is 4 °C, resulting in lower impact of the power outage compared to the old building. The P_{min} is 17.5 °C and the DoD is 0.138, which is lower than the new building. This shows that the degree of disturbance is low for new the building.
- As a conclusion, the old building performed worst in terms of energy resilience. It had a shorter robustness period, lower habitability period and lower minimum temperature. Moreover, it has high IoE, high SoC and high DoD compared to the new building.

Similar method, framework and indicators metrices can be used for other buildings and climate conditions to study the energy resilience of the buildings. Here are some challenges and obstacles that need to be considered and studied when thinking about estimating the performance of the energy-resilient building:

1. The interaction between the building's energy system and the user behavior is complex, and there are multiple energy flows within the building and outside the boundary, hence detailed models are needed.
2. The dynamic nature of the building with respect to the weather is complex, and multi-scale variations of climate can impact the performance.
3. Uncertainties in the climate, policy and economic recession and energy crises impact the reference case scenario.
4. Heavy calculation and computation cost is included.
5. Lack of standard calculation methods, regulations, energy models and climate models for energy and resilience studies.
6. Undefined and unclear definitions/indicators for resilience in various climatic zones and regions.
7. Lack of methods to design, model, optimize and assess the energy system for energy-resilient buildings that consider the future challenges.
8. The minimum thermal comfort limits, temperature thresholds and survivability power requirements need further studies based on the local requirements and climate.

Improved policy and research are needed at the national Finnish and the European levels that shall provide guidelines to society, businesses, authorities and end users to build energy-resilient buildings. This would include the improvement of the present building regulations and codes to include the minimum thresholds and requirements for resilience based on the human health perspective. It could also include a comparative resilience performance rating system, which can classify the building stock according to the resilience features. Hence, future buildings shall be designed to meet the requirements for the occupants' health and health cost. There is an important need to introduce new concepts that shall integrate energy resilience with energy flexibility.

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