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Thermal resilient buildings: How to be quantified? A novel benchmarking framework and labelling metric

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ABSTRACT

The resilient building design has become necessary within the increasing frequency and intensity of extreme disruptive events associated with climate change. Since thermal comfort is one of the main requirements of occupants, evaluating building resilience from a thermal perspective during and after disruptive events is necessary. Most of the existing thermal resilience metrics focus on thermal performance only during disruptive events. Building designers are still seeking metrics that can capture thermal resilience in both phases (i.e. during and after the disruptive events). This paper introduces a novel benchmarking framework and a multi-phase metric for thermal resilience quantification. The metric evaluates thermal resilience concerning building characteristics (i.e. building envelope and systems) and occupancy. It penalises for thermal performance deviations from the targets based on the phase, the hazard level , and the exposure time of the event. The introduced methodology is validated by quantifying the thermal resilient performance of six building designs against a four-day power failure as a disruptive event. The six designs represent minimum and passive building requirements with and without batteries or photovoltaics as resilience enhancement strategies. For the considered case study, upgrading the building from the minimum to the passive design has a huge impact (71%) on resilience improvement against power failure in winter. The application of the battery and PVs can improve the thermal resilience of the two designs in the range of 19%–27% and 44%–60%, respectively. Findings can provide a useful reference for building designers to benchmark the building's thermal resilience and constitute resilience enhancement measures.

1. Introduction

1.1. Scope

Building performance (including energy and comfort) can be affected by a wide range of foreseen and unforeseen changes during operation, such as environment effects (e.g. extreme weather due to the climate change [1]) or new requirements (e.g. new technologies or policies [2,3]). Buildings as facilities with significant investment costs should be able to react to these changes and maintain their performance and functionality. For this reason, interest has been growing to push the building designs beyond the minimum standard requirements to meet performance targets even under future changes [4]. In general, one strategy for adequate future building performance in the face of changes and disruptive events is mitigation in the form of protection [5]. Recently, in this approach, attention is being paid to the concept of resilience, which involves "low probability high impact scenarios". The report of Intergovernmental Panel on Climate Change (IPCC) [6] shows that the severity and frequency of these scenarios, such as natural disasters, are expected to increase in the following years because of climate change. In comparison to the pre-industrial era, extreme heat events are occurring more frequently, lasting longer, with greater intensity. For instance, the average number of heatwaves in the United States (US) has increased from two in 1960 to six in 2010 [7]. Based on the report of the Copernicus Climate Change Service, 2019 was the warmest year on record for Europe, with June as the hottest month on record [8].

Furthermore, in the past decades, climate change has increased the frequency and severity of extreme cold events, such as windstorms and snowstorms [9]. A recent example is the record of low temperatures during the 2021 winter in Texas, US. The low temperatures were followed first by snow and then by the blackouts, leaving millions of people without access to electricity during the COVID-19 pandemic [10]. Such events can, on the one hand, disturb the energy generation systems and, on the other hand can lead to thermal

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Nomenclature

A_{AF}	Total floor area
A_z	Area of each zone
EPC	Energy performance certificates
i	Segment counter
IOD	Indoor overheating degree
IPCC	Intergovernmental Panel on Climate Change
PV	Photovoltaic panel
RCI	Resilience class index
SFP	Specific fan power
S_i	Area of segment i
t	Time
t_0	Disturbance start time
t_1	Disturbance end time
t_2	Test end time
t_d	Delay time
TEK	Norwegian building regulation
T_{HT}	Temperature threshold for habitability
T_{min}	Minimum temperature during test period
TMY	Typical meteorological year
t_R	Recovery time
T_{RT}	Temperature threshold for robustness
T_{SP}	Setpoint temperature
U	U-Value
WUMTP	Weighted unmet thermal performance
$WUMTP_{Overall}$	Overall weighted unmet thermal performance
$WUMTP_{Overall,ref}$	Overall weighted unmet thermal performance of the reference building
W_E	Exposure time penalty
W_H	Hazard penalty
WHO	World Health Organization
W_P	Phase penalty
z	Zone counter

discomfort in buildings. In developed countries, more than 87% of time is spent indoors [11], and indoor thermal comfort is one of the main requirements of building occupants. A survey-based study shows that disruptions in acoustic quality and thermal comfort are the most disruptive factors, which can affect the productivity of buildings occupants [12]. This highlights the evaluation of building performance resilience from a thermal perspective. The report of the European Network of Transmission System Operators shows significant growth in grid disturbance (30%–60%) caused by environmental factors in the Nordic regions [13]. These phenomena, in parallel with the penetration of electrification in buildings, can cause huge losses [14] in the building sector. So, resilient building design against these inevitable events is imperative. In this paper, the building is defined to be resilient if it is able to prepare for, absorb, adapt to and recover from the disruptive event [15]. The building response after facing a disruptive event can be divided into two phases: (i) during the disruptive event and (ii) after the disruptive event. So far, some efforts have been made to improve building resilience, but quantifying these improvements during both phases (i.e. during and after the disturbance) still requires more research. In cold climate countries, such as Norway, a large share of annual energy consumption in buildings is related to the heating seasons [16], in which the heating demand is provided for the building. So, evaluating a building's thermal resilience during heating seasons is important. Furthermore, it is assumed that during the low probable high impact events, which are needed for resilience evaluation, people will spend most of their time at homes and this highlights the evaluation of thermal resilience for residential buildings. For these two reasons, this study will focus on evaluating the thermal resilience of residential buildings during heating seasons. It is noteworthy that the developed methodology in this study can be used for thermal resilience evaluation during the heating seasons in any geographical area that the building demands heating.

1.2. Resilience quantification

In general, several works have focused on the resilience assessment of systems in various fields. Hosseini et al. [5] separated resilience assessment approaches into two major categories: qualitative and quantitative. The qualitative approaches are based on assessing resilience without numeric descriptions. Methods such as conceptual frameworks and semi-quantitative indices can be placed in this group. In the field of the built environment, Sharifi and Yamagata [17] developed a conceptual framework for assessing urban energy resilience. In another framework, Nik et al. [18] divided the characteristics of resilient urban energy systems into four main groups: planning and preparation, resisting, adapting to and recovering from.

The quantitative approaches assess resilience with respect to numeric descriptions and are divided into two subcategories: general and structural-based modelling. The general approaches are based on empirically observable metrics of system performance without considering specific system characteristics. The resilience triangle developed by Bruneau et al. [19] in the field of seismic resilience is the most representative general-based method, which uses the total impact (i.e. performance losses during and after disruptions) to measure seismic resilience. The resilience trapezoid model [9] is another well-known general-based method, which considers the degraded state that the system experiences when facing a disruptive event. Panteli and Mancarella [20] were the first to use the resilience trapezoid for quantification grid resilience by the introduction of a set of time-dependent metrics called the $\Phi \Lambda E \Pi$ metric system, which is based on the speed Φ and the magnitude Λ of the damaged grid functionality, the duration of the damaged state E, and the recovery speed Π.

In the context of the built environment, Homaei and Hamdy [15] have adjusted these metrics for the quantification of different resilient abilities (i.e. preparation, absorption, adaptation, recovery). Li et al. [21] evaluated the impact of energy storage systems for health care centres facing power failure during the pandemic using the total impact approach and introducing a resilience index (the ratio of the supplied electric load to the total amount of electric load over a year). Shandiz et al. used the resilience trapezoid and time-dependent resilience metrics for evaluating the energy resilience of communities [22].

In structural-based approaches, system characteristics and behaviour need to be modelled or simulated to examine how the system's structure can influence its resilience. Simulation models are structural-based approaches in which simulations are used to represent uncertain behaviour of the system in resilience quantification [23]. For the built environment, dynamic building performance simulations are vital in the estimation of the building performance during normal and abnormal conditions. For example, Katal et al. [1] calculated the building thermal resilience in terms of winter passive survivability for the 1971 Montreal snowstorm by combining CityFFD (City Fast Fluid Dynamics) and CityBEM (City Building Energy Model) simulations. O'Brien et al. [24] used Energy Plus building performance simulation software for simulating the performance of high-rise residential buildings in Canada in case of power failure during winter and summer. They applied passive survivability and thermal autonomy as metrics for resilience evaluation.

Resilience metrics are essential in the quantification of resilience based on simulation results. Specific criteria should be considered regarding resilience metrics, such as repeatability and comparability [25]. Furthermore, resilience quantification needs to not only capture resilience during the disruptive event, but also after the disruptive event. The metric should also indicate how far and for how long the building performance is deviated from the targets. In other words, the metric should be sensitive to the hazard level and exposure time to the disruptive event.

Some typical simplified metrics have been used in the context of a building's thermal resilience based on simulation results. For instance, overheating risk [26,27] and heat index [28,29] are most used for evaluating building thermal resilience against disruptions like climate change and heatwaves. Another two simplified metrics that have been developed recently are passive survivability [1,24,30] and thermal autonomy [24]. The main issue with these simplified metrics is that they need to be used in the scale of one thermal zone and cannot unfold the resilience in the building level, called overall thermal resilience in this paper, which considers all zones of the building. To overcome this issue, Hamdy et al. [31] introduced a new index called IOD (indoor overheating degree), which considers different thermal comfort limits depending on the zone and takes the intensity and frequency of overheating into account. Furthermore, simplified metrics such as passive survivability and thermal autonomy only focus on thermal performance during the disruptive event. So far, little progress has been made on developing metrics that capture resilience in both phases of the disruptive event. Therefore, crucial information related to the post-event phase and building recovery can be lost. Putting together the literature on the resilience quantification approaches and metrics in the field of building thermal performance provides insights on the importance of resilience quantification with an appropriate set of metrics. These metrics should help benchmarking of different designs from resilience perspective in more informative and easy to understand approaches. Therefore, this work introduces a new multi-phase metric for quantifying the building overall thermal resilience (i.e. thermal resilience of whole building).

1.3. Contribution of this paper

As described above, the frequency and severity of extreme events increase because of climate change. Therefore, resilient building design is essential to face disruptive events. This paper introduces a methodology to quantify the overall building thermal resilience in case of disruptive events. The methodology aims to (i) develop a test framework for building thermal resilience quantification, (ii) quantify the overall thermal resilience for buildings, (iii) label the building thermal resilience, which can be included in energy performance certificates (EPCs) [32]. A new single metric for resilience quantification, called the weighted unmet thermal performance (WUMTP), is defined within the proposed methodology and allows the identification of the building resilience class. Indeed, the main novelty of this work is the introduction of the resilience test framework and quantification metric, with which a single value can summarise and weight all aspects affecting the building thermal resilience. There are two main considerations for this metric:

- The boundary conditions for metric quantification with respect to the building is focusing on building characteristics (including building envelope and systems) and occupancy in multi-zones with different thermal condition limits. This means that the developed metric can capture the changes in thermal resilience based on variations of these conditions not only for one zone but also for the whole building.
- The scope of metric quantification with respect to the disruptive event focuses on the phase of the event, the hazard level of the event, and the exposure time to the event. Changing one of these factors can affect the thermal resilience of a building.

As stated before, the scope of the developed test framework was on evaluating the thermal resilience of residential buildings during heating seasons. Residential buildings have been selected here because it is supposed that during the abnormal condition, which is needed for resilience evaluation, occupants will spend most of their time at homes. In Norway as a country with a cold climate, buildings are mostly heating dominated. For this reason, the suggested metric with the developed test framework was assessed for a case study of a Norwegian single-family house with two different designs which appropriately fits the scope of this study. Furthermore, the impact of design options and resilience enhancement strategies, such as battery storage and a photovoltaic (PV) system, on thermal resilience was evaluated. The paper is structured as follows. Section 2 describes the development of the test framework for the building thermal resilience evaluation. In addition, the thermal resilience quantification, WUMTP formulation, and resilience classification and labelling are described. In Section 3, the case study building is described along with different building designs and resilience enhancement strategies. Section 4 presents the results of the application of the resilience quantification and labelling methods for the case study. The impact of two resilience enhancement strategies was evaluated for the case study building. The paper concludes by outlining the practical implications of resilience quantification in building thermal performance predictions and explaining how this quantification of resilience can be helpful for building designers and decision-makers (Section 5).

2. Methodology

2.1. Multi-phase resilience curve associated to an event

In general, the performance of systems concerning a disruptive event as a function of time can be shown by two concepts: resilience triangle [19] and resilience trapezoid [9], which have widely been used in different fields such as seismic engineering, power engineering, etc [9,19]. The concept of the resilience triangle is the foundation for the analytical assessment of resilience, and it describes the deterioration of a system's functionality over the disruptive event timeline [33]. In this concept, immediate restoration actions are assumed to be taken at the end of the disturbance. The concept of the resilience triangle has been extended by resilience trapezoid, which considers the degraded state that the systems experience when facing a disruptive event. Being inspired by these two concepts, analysis of pre-simulation results of building performance during a disruptive event shows that buildings as dynamic systems are experiencing an exponential degradation when they are faced with disruptive events. So, in this paper, the performance of building concerning a disruptive event as a function of time is plotted with a curve. Similar to the resilience triangle [19], immediate restoration actions are assumed to be taken at the end of the disturbance. The plotted curve named the "multi-phase resilience curve" because of the two phases of the disruptive event — phase I, namely "during the disruptive event", and phase II, "after the disruptive event". Furthermore, two states are also represented in the multi-phase resilience curve to show the performance of building in initial and final states. Based on the definition of resilient buildings, the building is able to prepare in the initial state, absorb and adapt during the disruptive event (phase I) and recover after the disruptive event (phase II). The multi-phase resilience curve is a simulation-based curve. The performance of building in the initial state, during and after the disruptive event, and in the final state has been simulated by modelling the building using a dynamic whole building simulation tool. Building simulation has been selected here because it creates the possibility of easily controlling building boundary conditions and evaluating building performance under the disruptive event, which is not an easy task when it comes to the experimental methods. The performance of the building is simulated under a typical metrological year (TMY) weather file, which can properly show the most typical pattern of weather during a year. Furthermore, the disruptive event applies during a specific part of the heating season, for a specific time period, which will be elaborated later in Section 3.2. By running the building performance simulation during the period of the multi-phase resilience curve, performance of the building during the normal and abnormal conditions (i.e., states and phases) will be determined and form the multi-phase resilience curve. The implemented building performance simulation tool in this work is IDA Indoor Climate and Energy software (IDA ICE) [34], which applies equation-based modelling in Neutral Modelling Format (NMF) and has been validated using several validation tests [35,36]. The performance across different phases in the multi-phase resilience curve can be quantitatively measured by the application of suitable indicators of various performance criteria. Here, the "building indoor operative temperature" resulting from the simulation was used as a performance indicator to create the multi-phase resilience curve for the thermal resilience evaluation. It is noteworthy that other important factors such as humidity can influence the evaluation of thermal resilience, but in this study for the sake of simplicity thermal resilience has only been evaluated concerning the temperature. The indoor operative temperature is what humans perceive thermally in a space; it is a simplified measure of human thermal comfort derived from the mean radiant temperature and air temperature [37]. Furthermore, the curve experiences different temperature thresholds in case of a disruptive event. The conceptual illustration of the multi-phase thermal resilience curve, along with states, phases, and different performance thresholds, is shown in Fig. 1. Solid lines in this figure represent a fixed parameter, while dashed lines are case-dependent variables. The states and phases can be described as follows:

- Initial state ($0 \leq t < t_0$: In this state, the building operates based on the set point temperature (which is considered the target) before the disruptive event. Based on the resilient building definition, the building is preparing for the disruptive event in this state.
- Phase I($t_0 \leq t < t_1$): This phase is placed between the initiation and the end of the disruptive event, during which the indoor operative temperature is usually decreasing continuously. Based on the definition of resilient building, the building absorbs the impact of and then adapts to the disruptive event in this phase.
- Phase II ($t_1 \leq t < t_2$): This phase starts after the end of the disruptive event and lasts until the building reaches to the same performance level in initial state. During this phase, the indoor operative temperature is usually increasing continuously. Based on the definition of the resilient building, the building recovers from the disruptive event in this phase.
- Final state ($t > t_2$): This state starts after the full recovery of the building. In this state, the building operates based on the setpoint temperature like in the initial state.

In addition to these phases and states, four different performance thresholds are in the multi-phase thermal resilience curve:

- T_{SP} is the set target (the setpoint temperature), which is needed for the desired performance of the building.
- T_{RT} is the performance robustness threshold. Any performance (i.e. operative temperature) higher than this value will indicate a robust performance, and if the operative temperature is less than T_{RT}, the performance will not be robust from the thermal point of view.
- T_{HT} is the performance threshold for habitability. Any performance (i.e. operative temperature) lower than this value will create an uninhabitable condition for the building occupants.
- T_{min} is the minimum experienced performance (i.e., operative temperature) during phase I.

By considering these four performance thresholds, three performance levels are created. Values between T_{SP} and T_{RT} indicate an acceptable performance (acceptable level). Between T_{RT} and T_{HT}, the performance will be in the habitable level, and any value less than T_{HT} indicates an uninhabitable level. Every level is shown with a different colour in Fig. 1.

To quantify building thermal resilience based on a multi-phase resilience curve, a test framework is introduced in the next section, establishing the requirements for thermal resilience quantification.

2.2. Resilience test framework

The purpose of the thermal resilience test framework is to determine the effect of a given disruptive event with a fixed duration on the building thermal performance. In developing each test framework, three factors should be considered:

1. The disruptive event (The occurrence time (t_0) and the event duration($t_1 - t_0$)): Literature shows that various source of disruptive events such as fires, windstorms and hurricanes, flooding, heatwaves, ice storms, power outage, and the pandemic situation can influence building performance [38]. In the suggested test framework, it is assumed that the disruptive event will last during a fixed duration. This fixed duration and the initiation time of disruptive event are important parameters that should be considered when developing a test framework.
2. Duration of phase II ($t_2 - t_1$) — The thermal performance of the building after the disruptive event should also be simulated in order to determine how can it recover after the disruptive event. For the suggested test framework, it is assumed that phase II will last as long as phase I to capture how the building recovers from the disruptive event. During this phase, the time duration that takes the building to reach its pre-disturbance state called recovery time, and shown with t_R in Fig. 1. t_R shows how fast the building can recover from the disruptive event.
3. Performance levels: The range of different performance levels that have been defined in the previous section should also be specified when developing the test framework.

The suggested resilience test framework involves a fixed-duration disruptive event and simulates the performance of the building during and after the disruptive event. The application of an appropriate set of metrics for the developed test framework leads to thermal resilience quantification.

2.3. Thermal resilience quantification

2.3.1. Boundary conditions with respect to the building

In this paper, a new metric WUMTP was developed for thermal resilience quantification. WUMTP is a multi-zone metric that not only focuses on phase I but also represents the thermal performance during phase II. This metric can capture the abilities of absorption and adaptation during the disruptive event and recovery after the disruptive event. However, WUMTP does not capture the ability of preparation directly, but preparation affects the other abilities by default. For instance, if the building is more prepared for the disruptive event, it can absorb and adapt better and recover faster from the disruptive event. Furthermore, the focus of this metric is the thermal resilience of the whole building level and not focusing on the individual abilities. Unlike the previously mentioned metrics (e.g. overheating hours at a specified temperature), WUMTP is introduced so that different levels of thermal conditions for different zones can be considered, taking into account specific hours when the building is occupied. The boundaries of the thermal resilience evaluation are kept within the building characteristics (including building envelope and systems) and also the occupants who are using the building, as shown in Fig. 2. WUMTP is determined by calculating the thermal performance deviation from the temperature targets during the occupied hours and penalising them based on where they have been placed in the test framework. A lower WUMTP indicates the building is more thermal resilient.

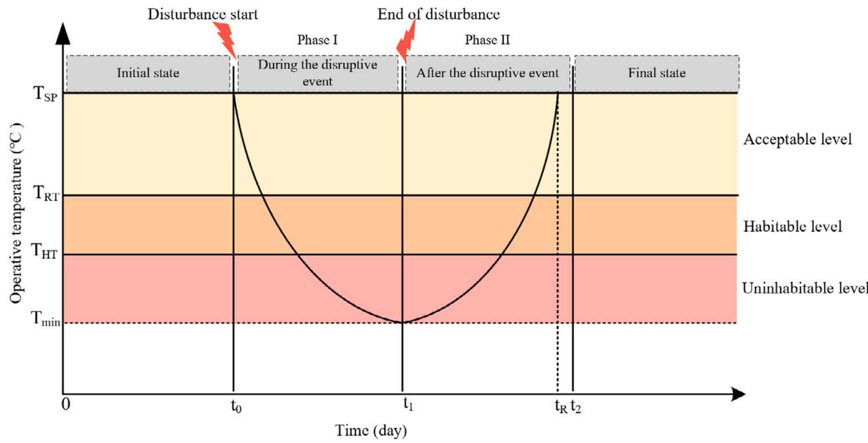

Fig. 1. Illustration of multi-phase thermal resilience curve of buildings.

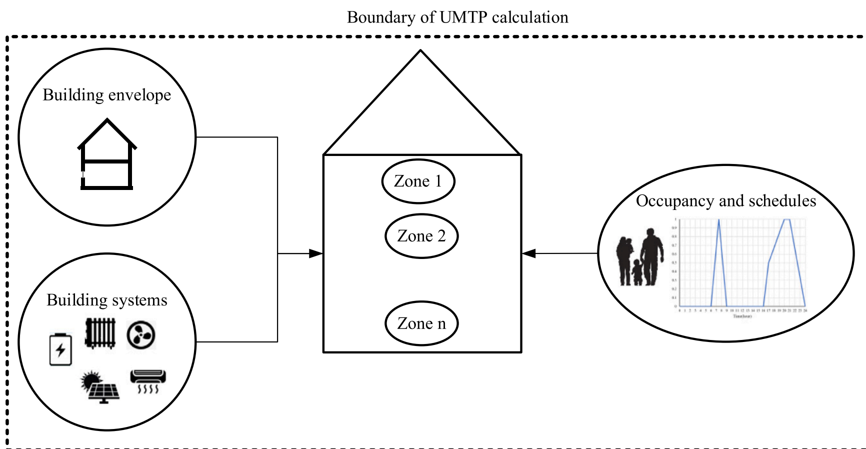

Fig. 2. Illustration of the boundary of WUMTP calculation.

2.3.2. Scope with respect to the event

The calculation of the WUMTP varies in the different phases and thermal performance levels of the test framework. Furthermore, the calculation of WUMTP is not the same for different exposure times within each level. For instance, the first few hours inside the uninhabitable level have a different impact in comparison to the remaining hours. The new metric is, therefore, more sensitive regarding the performance deviation in different parts of the resilience test framework. The quality of performance deviation in different parts can be differentiated by penalising it regarding the following factors, which indicate the scope of WUMTP quantification with respect to the event:

1. The phase of the event differentiates between the WUMTP in phases I and II. The toleration of the performance deviation during the disruptive event is more difficult in comparison to after the disturbance. This is a result of the mental condition that the occupants may experience during each phase. In phase I, the temperature is continuously decreasing, and occupants are facing a pessimistic condition. In contrast, in phase II, the temperature increases continuously, and occupants are facing an optimistic situation, which is easier to bear. The application of different penalties to these phases means the calculation of WUMTP is different as well.
2. The hazard level of the event differentiates between three different performance levels (acceptable, habitable and uninhabitable). The calculation of WUMTP in each of these levels differs with the application of various penalties.
3. The exposure time to the event: which differentiates the WUMTP in different exposure time duration. This differentiation creates two various sections (i.e., easy and difficult exposure sections) inside each phase and level, in which different penalties will be applied for them.

2.3.3. WUMTP metric

The application of two phases, three hazard levels and two exposure time sections results in 12 segments in the resilience test framework, as shown in Fig. 3. The lighter version of each colour indicates the easy exposure sections, and the darker version shows the difficult exposure sections in each level. Three penalty types are needed to be considered for each segment: phase penalty, hazard penalty, and exposure time penalty. The details of these penalties are shown in Table 1. The assigned values for each penalty in Table 1, are based on the logical assumptions that have been made by authors. To the best of the authors' knowledge, little is known in this context in the literature, and establishing a set of penalties still needs further attempts in the field of physiological research. When defining the phase penalty, the hazard level penalty, and the exposure time penalty for each segment, it should be noted that where the segment has been placed. For example, a segment in phase I will get a higher phase penalty in comparison to phase II. Regarding hazard level penalty, a segment in uninhabitable level will be penalised more in comparison to the habitable level, and that will be penalised more in comparison to the acceptable level. When it comes to the exposure time penalty, it should be noted where the segment has been placed regarding the phase, hazard level, and exposure time. The phase penalty is assigned as 0.6 for phase I and 0.4

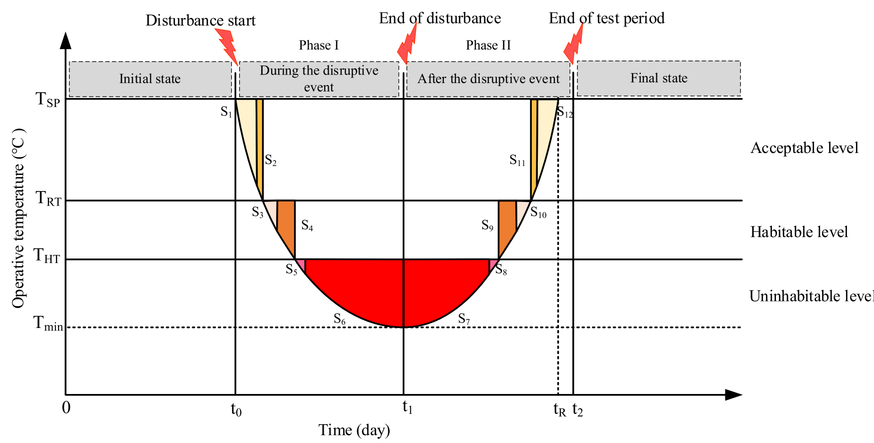

Fig. 3. Differentiation of 12 various segments in resilience test framework.

Table 1
Associated penalties for different segments inside the resilience test framework.

Segment	Penalties		
	Phase penalty (W_P)	Hazard penalty (W_H)	Exposure time penalty (W_E)
S1	0.6	0.1	2
S2	0.6	0.1	8
S3	0.6	0.2	10
S4	0.6	0.2	20
S5	0.6	0.7	20
S6	0.6	0.7	40
S7	0.4	0.7	40
S8	0.4	0.7	20
S9	0.4	0.2	20
S10	0.4	0.2	10
S11	0.4	0.1	8
S12	0.4	0.1	2

for phase II. A hazard penalty of 0.1 is applied for an acceptable level, and 0.2 and 0.7 for the habitable and uninhabitable levels, respectively. The exposure time penalty is different for each section in each level. In order to obtain comparable and informative results from the WUMTP calculation, note that the exposure time penalty is not on the same scale as the two previous penalties. For example, in phase I and in the acceptable level, the assigned penalty for S_1 (easy exposure) is 2, and for S_2 (difficult exposure) is 8. The summation of exposure time penalties in each phase is 100. The assigned penalties can be changed easily based on the priorities of each phase, the hazard level and exposure time.

Considering the specified penalties in Table 1 and the area of each segment resulted in the simulation-based test framework, the definition of WUMTP for a single zone (WUMTP) will be as follows:

$$WUMTP = \sum_{i=1}^{12} S_i W_{P,i} W_{H,i} W_{E,i} \qquad \text{[Degree hours]} \tag{1}$$

where i is the counter for 12 segments and S_i shows the area of segment i during the occupancy hours, which has been calculated based on the hourly indoor operative temperature resulted in the building performance simulation. $W_{P,i}$, $W_{H,i}$ and $W_{E,i}$ represent the phase penalty, the hazard penalty and the exposure time penalty of the segment i, respectively. Inside each segment, only occupied hours are accounted for in the calculation of the segment area. A building consists of different thermal zones, and different performance levels can be defined based on standards or even the occupants' desires for each zone. WUMTP allows the consideration of these performance levels separately for each zone, but one overall metric is needed to evaluate the overall building. Based on the calculated WUMTP for each zone, the overall WUMTP of the building can be calculated based on the following equation:

$$WUMTP_{Overall} = \frac{\sum_{z=1}^{Z} WUMTP_z}{\sum_{z=1}^{Z} A_z} \qquad \text{[Degree hours/m}^2\text{]} \tag{2}$$

where z is the building zone counter, Z is the total number of zones in the building, and A_z is the area of each zone.

2.4. Resilience labelling

In order to rate a building in a specific resilience class, the same approach as energy labelling is used. The objective of building energy labelling is to unfold the building's energy consumption and to promote potential energy-saving measures. Building energy labelling consists of assigning an energy performance label to buildings and it is based on the development of a scale for the labelling index. Since its introduction in early 2000, the scheme has been used to classify buildings on a scale from A to G, with A-rated buildings the most energy-efficient and G the least [39]. The energy labelling can be evaluated based on the simulated or measured energy performance of buildings [40]. Energy labelling based on calculations is mostly used for the new buildings, while energy labelling based on the measurements is used for the existing buildings. In the energy labelling method, first, the energy performance of a reference building, which is derived from the actual building, but is according to standards and regulations is evaluated. In the second step, the performance of the actual building will be evaluated and be compared with the reference building. The next step is to assign a label, and this needs the development of a scale related to the labelling index. The labelling index is the ratio of the energy performance of the actual building to the energy performance of the reference building. Limits between labels can be set on a scale [39]. The same strategy has been used for the resilience labelling of the buildings in this study. The steps toward this approach are shown in Fig. 4. The first step is to select one ideal reference building design based on the standards or regulations. The characteristics of this reference building regarding building envelope, systems, occupancy schedules and internal load can be defined based on the recommendations from standards in each country. The second step is to select the building design to be rated for resilience. In the third step, the location of the building should be selected. Both the reference building and the building of interest should be located in the same place. In step 4, both the reference building and the desired building are subjected to the same test framework, such that they are exposed to the same disruptive event, starting at a specified time and lasting for a specified duration. Step 5 deals with the selection of the thermal performance levels for the different zones of the building. In steps 6 and 7, the $WUMTP_{overall}$ is calculated for both the reference and desired buildings. The calculated

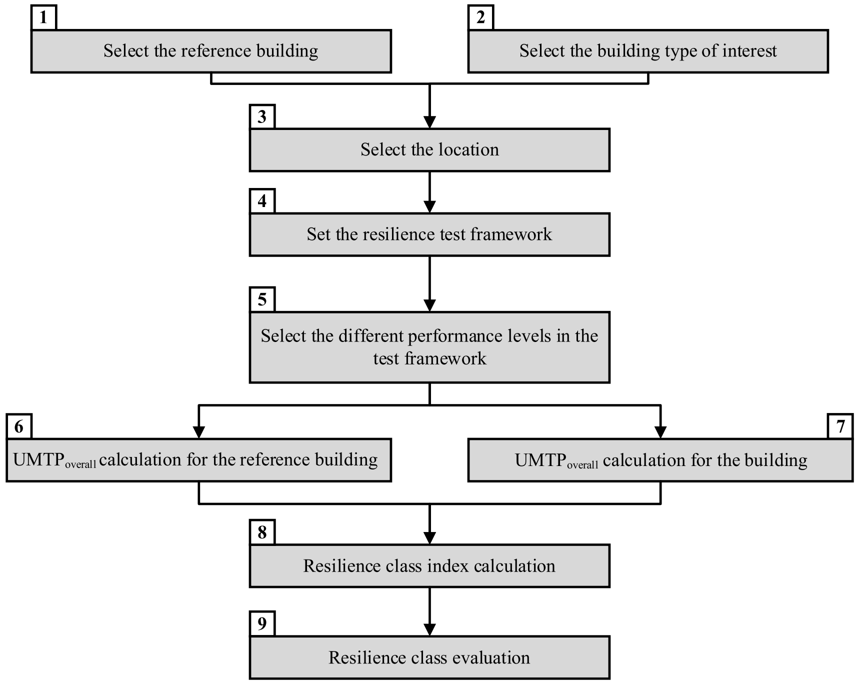

Fig. 4. Steps to implement resilience labelling methodology.

Table 2
Resilience classes for buildings labelling.

<3.6	RCI		Class A^+
<2.4	RCI	≤ 3.6	Class A
<1.5	RCI	≤ 2.4	Class B
<0.9	RCI	≤ 1.5	Class C
<0.6	RCI	≤ 0.9	Class E
	RCI	≤ 0.6	Class F

$WUMTP_{overall}$ for the reference building is assumed to have a medium WUMTP level, set in class C. In step 8, the resilience class index (RCI) is determined by dividing the $WUMTP_{overall}$ of the reference building by the $WUMTP_{overall}$ of the desired building as Eq. (3).

$$RCI = \frac{WUMTP_{overall,ref}}{WUMTP_{overall}} \tag{3}$$

In step 9, the resilience class of the desired design is determined as presented in Table 2, where the subdivisions are multiples of 0.3. The range of class D is 0.3, but the ranges of classes C, B, A increase to 0.6, 0.9, and 1.2, respectively. Therefore, switching from class B to A is more difficult than switching from class C to B.

3. Case study

The suggested methods for resilience quantification and labelling are demonstrated using a representative model of Norwegian single-family houses in order to analyse the impact of different building designs and resilience enhancement strategies on a building's thermal resilience.

3.1. Description of case study

A representative model of a Norwegian single-family house was selected to be studied [41]. It is a two-storey building with a floor area of 162.4 m^2, located in Oslo. The building model was divided into three thermal zones (living room, bedroom, bathroom) to simulate the performance of each zone from energy and comfort perspectives in a detailed model in IDA Indoor Climate and Energy software (IDA ICE) [34], which was validated using the BESTEST: Test Procedures [42]. The building is all-electric, equipped with direct-electric heating systems. The occupancy schedules are based on the Norwegian standard (NS3031) [43], and domestic hot water distribution and internal heat gains were based on [41]. Heating set points, window opening strategy and window shading aligned with the first scenario in [41], and the International Weather for Energy Calculations (IWEC) weather file from the library of IDA ICE was used for running the simulations. Two building designs and two categories of resilience enhancement strategies were considered for the case study building and are described in the following subsections.

3.1.1. Building designs

The two designs are based on the acceptable designs in the Norwegian standards. The first design, called "standard design" in this work, is based on the conventional Norwegian building code from 2017 (TEK17) [44]. TEK17 is the current minimum energy requirement in Norway. The second design, called "passive design" in this work, is based on the Norwegian passive house standard NS3700 [45]. The building element characteristics for the TEK17 standard and passive house standard designs are shown in Table 3. The TEK17 standard states that the total net specific energy use (kWh/m^2) – which includes space heating, heating for ventilation air, space cooling, domestic hot water, ventilation, lighting systems and appliances – for a single-family house is derived from the following equation [44]:

$$Net\ specific\ energy = 100 + \frac{1600}{heated\ floor\ area}\ [\mathrm{kWh/m^2}] \tag{4}$$

Considering this equation, the total energy use for the first design (standard design) of the case study building should not exceed 110 kWh/m^2.

Based on NS3700 [45], the annual energy used for space heating is based on the useful floor area and local annual mean temperature. For the case study building located in Oslo, the annual energy for space heating should be calculated based on the following equation [45]:

$$Annual\ space\ heating = 15 + 5.4 * \frac{250 - A_{FA}}{100}\ [\mathrm{kWh/m^2}] \tag{5}$$

Which A_{FA} shows the floor area in m^2. This equation set the annual space heating equal to 19.75 kWh/m^2 for the case study building.

Table 3
Building element characteristic for the standard and passive design.

	Standard design (TEK17 standard)	Passive design (Passive House standard)
U_{wall} [W/m^2 K]	0.19	0.12
U_{roof} [W/m^2 K]	0.13	0.09
U_{floor} [W/m^2 K]	0.1	0.08
U_{window} [W/m^2 K]	0.8	0.8
Thermal bridge [W/m^2 K]	0.07	0.03
Heat exchanger efficiency (%)	80	80
SFP ventilation [kW/m^3 s]	1.5	1.5
Air leakage 50 Pa [Air change/h]	0.6	0.6

Table 4
Heating capacity of different zones in the two designs.

	Heating capacity (W)	
	Standard design	Passive design
Living room	2000	1300
Bedroom	1300	900
Bathroom	900	600

Table 5
Cost-effective battery size for the standard and passive designs.

	Standard design	Passive design
Cost-effective battery size (kWh)	48	31

The heating capacity of each zone is compared for the two designs in Table 4.

3.1.2. Applied resilience enhancement strategies for the case study

Two categories of resilience enhancement strategies were evaluated for their impact on the introduced designs of the case study building. The first enhancement strategy is the application of batteries as the storage system, and the second is the implementation of the PV systems for the two building designs.

i. Batteries as a storage system

Literature shows that storage systems can be implemented as one of the resilience enhancement strategies in different scales such as grid scale or building scale. Even though small-scale batteries are still relatively expensive, they can be a potential solution to render home resilience [46]. For instance, Mehrjerdi [47] studied the impact of battery swapping mechanisms in a vehicle-to-home operation to evaluate the building energy resilience enhancement. Kosai et al. [48] investigated the role of storage capacity on the resilience of hybrid renewable energy systems. Homaei and Hamdy [49] proposed a new approach for battery sizing in all-electric buildings, called "cost-effective battery sizing". This sizing approach is based on the strategy of shifting heating demand in all-electric buildings based on a signal coming from dynamic pricing tariffs. Norwegian regulators proposed three business models of dynamic pricing tariffs to incentivise load shifts and peak load reduction [50]. Homaei and Hamdy [49] developed cost-effective battery sizing strategies for these three tariffs. In this work, the cost-effective battery size needed for shifting the heat load based on the "time of use" tariff was implemented as a resilience enhancement option. At the start of the disruptive event, batteries were assumed to be ready to use with full capacity. The evaluation of building thermal performance in case of battery implementation was performed with IDA ICE. First, the duration in which the battery capacity could provide the total space heating demand of the building, or "delay time (t_d), was calculated, i.e. the disruptive event was assumed to be delayed by t_d. This delay in the disruptive event will affect the thermal performance of the building during and after the disruptive event. It will absorb a part of the event's impact, and the minimum temperature will be higher compared to the case without a battery. The battery capacities based on cost-effective battery sizing for each of the two designs are reported in Table 5.

ii. Implementation of PV systems

Electricity generation from renewable sources, such as solar PVs, can provide resilience for buildings or, on larger scales, for grids. Even more effective is electricity generation from PV combined with storage systems. For example, Gupta et al. [51] evaluated the extent of energy resilience through the application of PVs and smart batteries at a community level. In the current work, the impact of PV systems on resilience enhancement was considered without storage systems. Hence, the generated electricity from PV systems, used only for space heating in the building, would be directly used during the disruptive event. A PV configuration with a total area of 40 m^2, which is typical for similar buildings [52], was added for the two suggested designs of the case study building to understand how the implementation of the PV system can be helpful in resilience enhancement.

3.2. Establishing the test framework for case study building: four-day test framework

As mentioned before, different disruptive events can be considered in the suggested resilience test framework. In this paper, the suggested test framework was applied for an all-electric case study building, and for this reason, a fixed duration of power failure was considered as the disruptive event. This power failure lasted for four days and took place during the four days with the highest heating demand (starting on 14 January). The resilience test framework is called the "four-day test framework" for the considered case study. The duration of power failure was specified based on iterative simulations, which showed how long a power failure needed to be to move a reference building (based on Norwegian standards) out of the habitability range. Furthermore, the same duration was used for phase II. To gain a full perspective of building performance in the initial and final states, these two states were simulated for a duration of one day. This means that the performance of the building was simulated for a total of ten days: one day in the initial state, four days during the power failure, four days after power failure and one day in the final state. Performance levels in the four-day test framework could be set based on the standards and regulations in Norway. In this paper, the four days test framework focused on a power failure as a disruptive event and implemented operative temperature as the performance indicator. This framework can be customised easily and used for other disruptive events and other performance criteria. As stated in Section 2, three performance levels are in the multi-phase resilience curve and consequently in the test framework. These performance levels are variant for each thermal zone in the building. The case study building had three thermal zones, and the performance levels for these thermal zones are described here:

- The first performance threshold is T_{SP}, which shows the setpoint temperature for each thermal zone. Acceptable heating set points in the Norwegian context were selected from [53] for different zones in the case study building. The setpoint temperatures for the living room, bedroom and bathroom were 21.5 °C, 18 °C, 23 °C, respectively.
- The second performance threshold is T_{RT}, which differentiates between the robust and non-robust performance. Based on the recommendations of the World Health Organization (WHO) [54], 18 °C is a safe and well-balancing temperature to protect the health of general populations during cold seasons in countries with temperate or cold climates. Therefore, 18 °C was selected as T_{RT} for the living room zone. This created a 3.5 °C margin from the setpoint temperature for the robust performance in the living room. The same margin was applied for other zones, resulting in a T_{RT} of 14.5 °C for the bedroom and 19.5 °C for the bathroom. Selecting different robustness threshold for different zones has been inspired by different setpoint temperature in each zone and based on the cultural habits that occupants may have. For example, in Scandinavia, more people prefer to have colder

Table 6
Three performance thresholds for different zones of the case study building.

Performance level	Zones		
	Living room	Bedroom	Bathroom
T_{SP} (°C)	21.5	18	23
T_{SP} (°C)	18	14.5	19.5
T_{SP} (°C)	15	11.5	16.5

bedrooms and instead they try to protect themselves by using warmer clothes and thicker blankets [55]. For this reason, it is assumed that occupants can tolerate colder temperature in bedrooms. The opposite is happening for zones such as bathrooms and this creates the idea behind assigning different robustness threshold for different zones.

- The last performance threshold is T_{HT}, which differentiates between habitable and uninhabitable condition for the occupant. A temperature of 15 °C was selected as the habitability threshold for the living room based on a comprehensive review on the effect of low temperatures on elderly morbidity [56]. This created a 3 °C margin from the robustness threshold for the habitable performance in the living room. The same margin was applied for other zones, resulting in T_{HT} of 11.5 °C for the bedroom and 16.5 °C for the bathroom.

The performance thresholds for the three different zones are summarised in Table 6.

Another factor in the test framework is the impact of exposure time to hazard, which is indicated with two sections: easy and difficult exposure. Literature shows that exposure between one to two hours to low temperatures, such as 10 °C [57], 11 °C [58] and 12 °C [59] (all of which are in uninhabitable levels), has a significant impact on human health, such as changes in blood pressure, a decrease of body temperature, changes in heart rate and decrease in plasma level [60]. Therefore, the easy exposure section in the uninhabitable level was assumed to last for one hour, and the rest formed the difficult exposure section. For the habitable level, the first two hours formed the easy exposure section, and the rest was the difficult exposure section. At the acceptable level, the easy section would last for three hours, and the rest was the difficult exposure section.

4. Result and discussion

This study considers four-days power failure as a low probable high impact event for the case study building and tries to quantify thermal resilience using a simulation-based test framework as one structural-based resilience quantification method. The results of the multi-phase resilience curve, resilience quantification, and labelling have been shown in the following sections:

4.1. Multi-phase resilience curve for considered designs

Fig. 5 represents the multi-phase resilience curve for the two designs: standard design (Fig. 5a) and passive design (Fig. 5b) in the living room zone. The thermal performances of these two designs with the enhancement strategies are also shown in Fig. 5. The standard design clearly experiences the uninhabitable level in its base condition (without using any resilient enhancement strategies) and in the case of using enhancement strategies. In contrast, the passive design does not experience the uninhabitable level even in its base condition. This shows that upgrading design from standard to passive design plays an important role in case of facing power failure during cold winter days. The blue curves in Fig. 5a and b show the design performance when the battery is used for storage capacity, and the effect of the battery is shown by the delayed period t_d that postpones the power failure. In the case of the application of the PV system, the temperature fluctuation

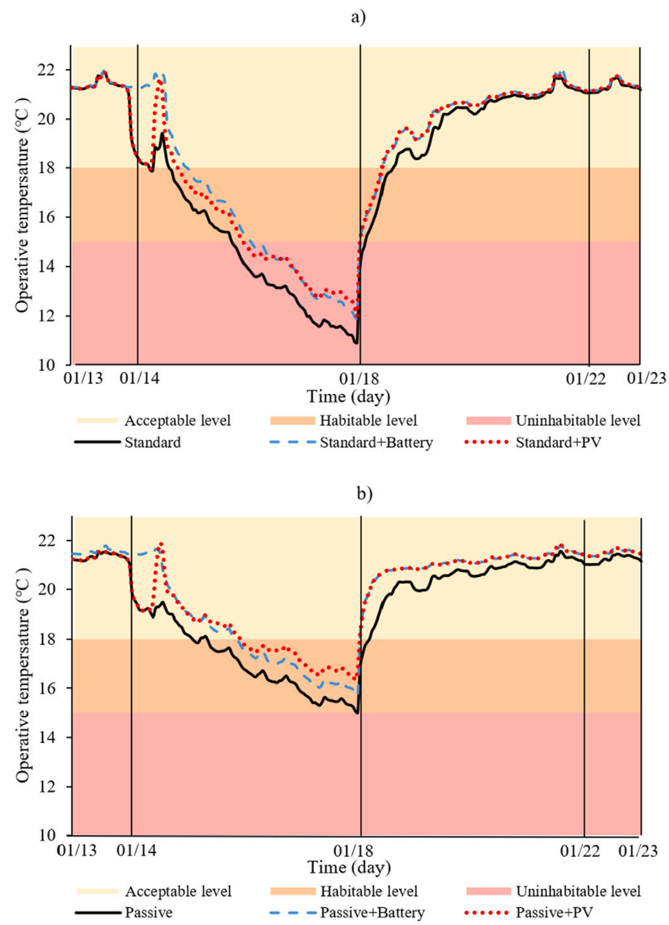

Fig. 5. Impact of the resilience enhancement strategies on the multi-phase resilience curve of (a) standard design, (b) passive design. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

in the daytime during the disruptive event shows the impact of the implementation of the PV system (red curves), which was providing electricity to be used directly for space heating demand in the building, and when the electricity production was high, the temperature increased even in the power failure condition. Furthermore, Fig. 5 shows that in both of the designs during phase II, the performances with the battery and with the PV system are approximately the same. The building designs with the battery and with the PV system are identical in phase II, and the minimum experienced temperature in these two cases are near to each other. Therefore, their performances during recovery would be similar. The effects of the enhancement strategies or design upgrade on the thermal performance of the building during the test days are described in detail in the following sections.

4.1.1. Building envelope influence

The influence of the building envelope on the multi-phase resilience curve was evaluated through the comparison of designs based on the TEK17 (standard design) and passive house standards (passive design), without the implementation of resilience improvement strategies. Fig. 6 shows the multi-phase resilience curve for the living room zone for the two designs based on TEK17 and passive house standards. The building envelope upgrade clearly had a huge impact on the resilience curve and consequently on the WUMTP calculation and resilience class evaluation. The multi-phase resilience curve of the standard design shows that this design experienced the uninhabitable level in the case of four days of power failure. In contrast, the passive house design did not experience the uninhabitable level in the case of four days of

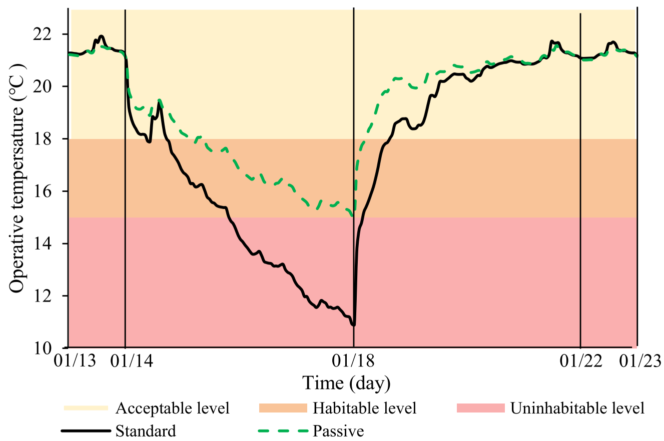

Fig. 6. Comparison of multi-phase resilience curve for standard and passive design without any enhancement strategies.

power failure in Oslo. The minimum temperature in the living room for the standard and passive designs were approximately 11 °C and 15 °C, respectively. Despite this difference, the recovery time (the time it takes to reach the set point temperature after the power failure) is approximately the same for both cases. This means that the recovery speed for passive design is slower than the standard design.

4.1.2. Battery storage influence

Fig. 7 clearly shows that implementation of the batteries as a storage system plays an important role when the building is facing an event that can disrupt its performance. To evaluate the impact of the application of battery storage in the case of a four-day power failure, the two building designs with and without a battery were compared, as shown in Fig. 7. In the standard design, the implementation of the cost-effective battery creates a delay time of 15 h and postpones the power failure for 15 h. A higher delay time results in a smaller temperature drop during the power failure. A 15-hour delay increased the minimum experienced temperature from 11 °C to 12 °C. Furthermore, the application of the cost-effective battery did not shift the resilience curve of the standard design out of the uninhabitable level. For the passive design, the application of the cost-effective battery leads to a 13-hour delay in the power failure, which increased the minimum experienced temperature from 15 °C to 15.7 °C. In addition, the application of the battery also did not change the experienced levels for the passive design. Therefore, even after adding the battery, the resilience curve still travelled through the acceptable and habitable levels.

4.1.3. PV system influence

The effect of the PV systems on the resilience of the two suggested designs was investigated. In this case, the generated electricity by the PV systems was assumed to be directly used for heating during the power failure and it will not be used any more after the power connection. The electricity production from the PV system during the ten-day test is shown in Fig. 8a. Only the electricity generation in the dark grey area was used by the building in the simulation. Fig. 8b and c show multi-phase resilience curves in the living room for the standard and passive designs with and without the PV systems. When the PV system was implemented, both standard and passive designs faced peak temperatures on 15 January. This peak in temperature aligned with the higher PV production the same day compared to the other days during the power failure. The application of the PV system for the standard design increased the minimum experienced temperature from 11 °C to 12.5 °C, without moving the resilience curve from uninhabitable level. For the passive design, the minimum experienced temperature increased from 15 °C to 16.5 °C. The minimum temperature difference in both standard and passive designs was 1.5 °C when the PV was added to the design as an enhancement strategy.

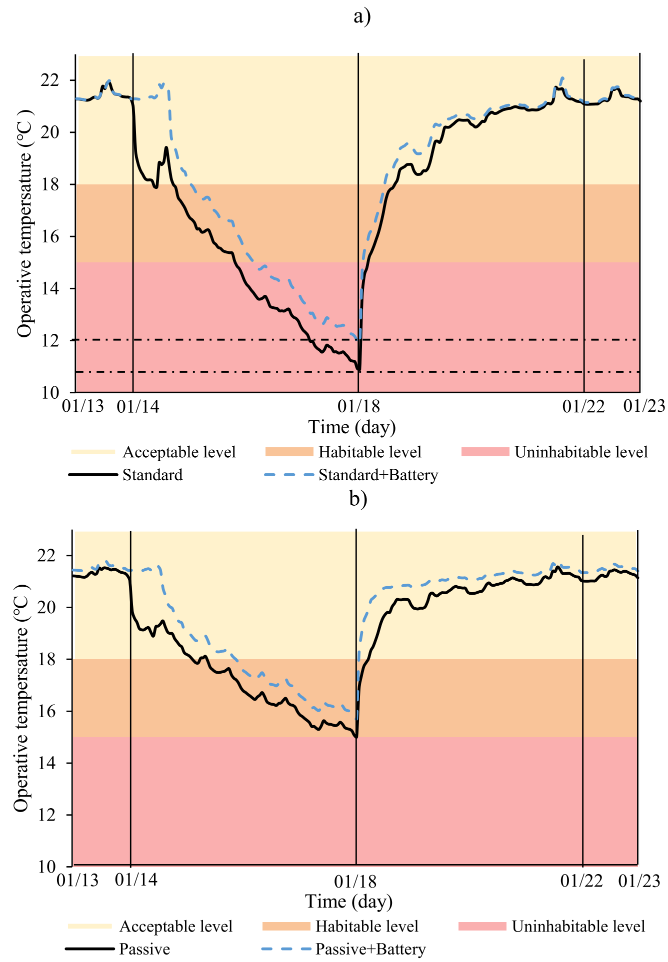

Fig. 7. Influence of the battery storage on the (a) standard design and (b) passive design.

4.2. Quantification of WUMTP

The metric for resilience quantification ($WUMTP_{overall}$) was calculated for the different designs of the considered case study. This metric is multi-zone, and three different thermal zones were in the case study building. Therefore, the suggested performance levels in Table 6 were used for the calculation of $WUMTP_{overall}$. The values of $WUMTP_{overall}$ are reported in Table 7 for the six designs. The upgrade of the standard design to the passive design decreased the $WUMTP_{overall}$ by 80 degree-hours, a 71% reduction. This means that in the case of power failure during cold winter days, the passive design performs more closely to the targets compared to the standard design. In this work, the suggested test framework and calculation of $WUMTP_{overall}$ focused on a cold event during winter. So, the WUMTP during summer was not evaluated here and is out of the scope of the considered test framework. However, it is possible to change the event type to a hot event, such as a heatwave, but the framework need specific adjustment regarding this kind of events. Although the passive design had a lower $WUMTP_{overall}$ than the standard design against a cold event, the situation may be different when a hot event is implemented in the test framework. The lower $WUMTP_{overall}$ of the passive design in the current test framework is not a surprising result and is in line with what was expected regarding the performance of standard and passive designs. Similar work has been done by O'Brien and Bennet [24] who tried to evaluate the impact of building envelope on the thermal resilience of Canadian high-rise residential buildings

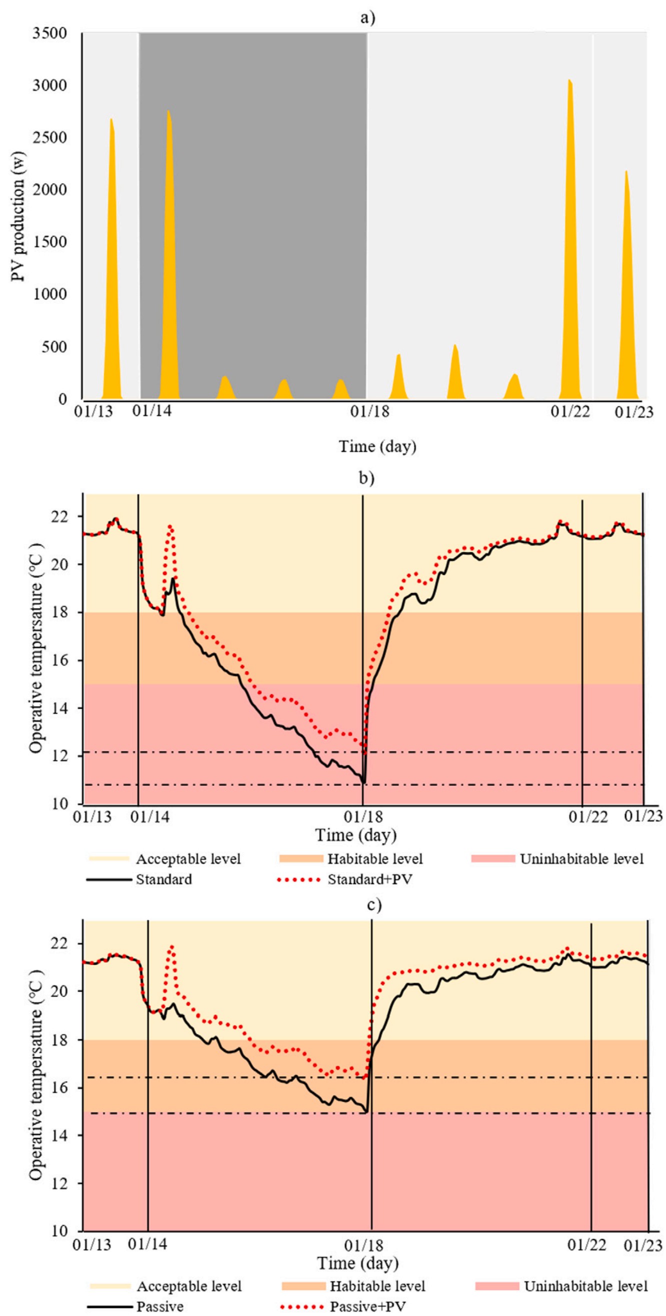

Fig. 8. (a) PV production during test days, (b) Influence of the PV system on the standard design, (c) Influence of the PV system on the passive design.

during power outages. They have used two metrics for thermal resilience quantification: passive survivability and thermal autonomy. They approved that the high-performance envelopes significantly reduce the frequency of conditions that are too cold, which is in line with our findings. However, passive survivability and thermal autonomy are only evaluating the performance of buildings during the event, and they have no considerations regarding after event phase. In addition, the passive survivability metric only considers the performance of building until the survivability threshold and it does not include any observation of building performance after survivability threshold, which has been captured by WUMTP metric. Furthermore, passive survivability and thermal autonomy do not reveal any information about the quality of performance deviations from the temperature targets. For example, they do not capture in which hazard level the performance deviations

Table 7
Calculated $WUMTP_{overall}$ for the six designs of the case study building.

Num	Design	WUMTP (Degree hours)	Improvement (Degree hours)
1	Standard	113	–
2	Standard+Battery	91	22 (compared to standard)
3	Standard+PV	63	50 (compared to standard)
4	Passive	33	–
5	Passive+Battery	24	9 (compared to passive)
6	Passive+PV	13	20 (compared to passive)

are placed and how easily or difficultly they can be tolerated. These issues tried to be shown by defining the hazard levels, and exposure times, and penalties in WUMTP. The developed test framework and calculation of the $WUMTP_{overall}$ considering the event phase, hazard levels, and exposure time helps the designers and decision-makers to compare designs and enhancement strategies, such as adding battery storage or PV systems.

Regarding the enhancement strategies, the addition of battery storage and PV systems decreased the $WWUMTP_{overall}$ for both standard and passive designs. For the standard design, the battery addition changed the $WUMTP_{overall}$ from 113 to 91 degree-hours, a 19% reduction. When PV was added to the standard design, the $WUMTP_{overall}$ changed from 113 to 63 degree-hours, a 44% reduction. For the passive design, the battery application decreased the $WUMTP_{overall}$ by 9 degree-hours (27% reduction), and the PV addition changed the $WUMTP_{overall}$ from 33 to 13, a drop by 60%. The absolute improvement values in degree-hours are higher for the standard design in the case of both enhancement strategies. Hence, if the building is less resilient (e.g. standard design), the improvements will be more significant. Furthermore, the result showed that the application of PV systems had a greater impact than the cost-effective battery storage for both standard and passive design for the considered case study. The resilience enhancements achieved by the application of PV systems and batteries in this study is in line with other findings in the literature. For example, Gupta et al. [51] confirm that the application of PV systems can enhance energy resilience at the community level. However, they have not mentioned that how they have quantified resilience and they have implemented more general measures related to PV such as self-consumption. Furthermore, their focus was more on energy resilience and they did not separate total energy to its subcategories such as heating, etc. Another example is the work of Mehrjerdi [47], who has tried to study the impact of batteries in the vehicle-to-home battery swapping mechanics. The result of this study also shows that batteries are able to improve resilience and reduce energy cost. The focus of this work is also on the resilience of total energy consumed in the building without separating it into subcategories. In this study, resilience is evaluated based on the number of hours in which the total energy demand of the building can be provided by batteries. Using this approach does not reveal any information about the different phase of the disruptive event and the level of hazard that the building can be exposed to.

4.3. Resilience labelling for the considered designs

The building designs were classified based on their resilience according to the resilience classes introduced in Table 2. As stated in Fig. 4, the first step for resilience labelling is to select a reference design for the considered building. For the considered case study building, design based on TEK 17 standard (standard design) [44], which is the minimum requirement in Norway has been selected as the reference design. The simulation of this design has been done under the recommendations of NS3031 standard [43] with respect to the internal loads, etc. This makes the RCI for the standard design to be equal to 1 and its resilience will be placed in class C as shown in Fig. 9. The RCI of other designs are also been calculated by dividing the $WUMTP_{overall}$ of

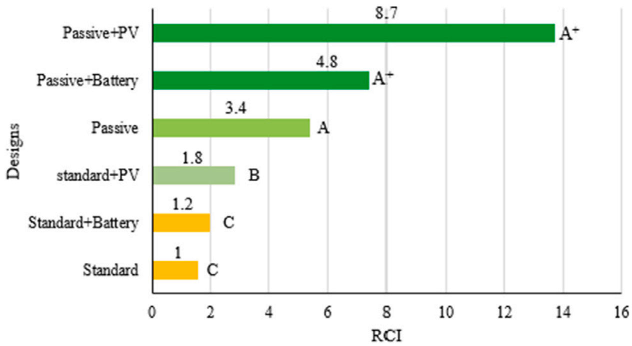

Fig. 9. Calculated RCI and resilience class for the combination of designs and enhancement strategies.

the reference design by the studied designs in this paper. According to Fig. 9 that adding the battery to the standard design does not changing the resilience class of the standard design . Furthermore, with the application of the PV systems, the resilience class of the standard design will be upgraded from class C to class B. The same building with the passive standards by itself is in resilience class A, and the application of the battery and PV systems moved the passive design to class A^+. The resilience classes of the six considered designs for the case study building are distributed from class C to A^+. The maximum resilience class improvement occurred when the design changed from standard to passive equipped with PV panels. Furthermore, if the standard design was upgraded to the passive design without any other improvement options, the resilience level would improve by two levels (from class C to A).

4.4. Strength and limitations

We are not aware of studies that aimed to evaluated thermal resilience on a building scale involving multiple phases of disruptive events, various hazard levels, and varying exposure times to the disruptive event. In addition, the suggested methodology creates a great potential for benchmarking the thermal resilience of residential buildings with respect to the building's characteristics and occupants. Despite its scientific approach, the methodology can be easily used by different stakeholders involving in real projects such as building designers, engineers, decision-makers, and even building occupants. However, we acknowledge that the methodology has some limitations, which should be mentioned: this methodology is focusing on the quantification of thermal resilience for residential buildings during heating seasons. The positive point regarding this methodology is that it can be implemented for thermal resilience quantification, wherever that there is a need for heating during cold seasons, but when it comes to evaluation of thermal resilience during the cooling season, the methodology needs to be adjusted and it may not be applicable for evaluation of thermal resilience during cooling seasons in, for example, regions with hot and humid weather. Further considerations regarding thresholds, penalties and etc needed to be considered with respect to the evaluation of thermal resilience during cooling seasons. Furthermore, this methodology only takes temperature into account in the evaluation of thermal resilience, while other factors such as humidity can also influence thermal resilience evaluation, which needs further research. In addition, the application of this methodology is limited to the residential buildings and its extension to other kinds of buildings such as educational buildings, office buildings, hospitals, and care homes can be achieved by setting a new set of assumptions regarding the thermal comfort conditions in each kind of these buildings.

5. Summary and conclusions

As a step toward protecting building performance against uncertainties, changes and disturbances, this paper proposes a methodology to quantify the thermal resilience of buildings and label these buildings according to their resilience level. The thermal resilience quantification is based on the introduction of a single metric, WUMTP, which calculates the deviation from the thermal targets for the whole building and penalises them based on three factors: the phase of the event, the hazard level of the event and the exposure time to the event. Given the dependency of resilience quantification on the scope of the disruptive event, a test framework was also developed for thermal resilience quantification, which considers the type and duration of the event, the time duration for each event phase, and different thermal performance levels. Furthermore, a whole-building dynamic performance simulation was also performed in order to easily control the boundary conditions of the building and predict the building performance during normal and abnormal conditions.

The developed test framework and new metric were used for a case study building of a Norwegian single-family house to determine how the building would perform during a four-day power failure during a typically cold winter. Two designs were considered for the case study building based on the Norwegian standards: a standard design, based on the TEK 17 standard (a minimum requirement in Norway), and a passive design, based on the Norwegian passive house standard. Furthermore, two resilience enhancement strategies – battery storage and PV systems – were considered to evaluate their impact on the designs thermal resilience.

- The developed test framework can guide building designers in establishing the requirements that are needed for resilience quantification. In this paper, the developed framework was used to evaluate thermal resilience in the case of power failure. However, different event types, performance criteria, and thresholds can be implemented for further evaluation.
- The developed metric for thermal resilience quantification is a multi-zone metric, which represents the thermal resilience for the whole building by considering different performance thresholds for different thermal zones inside the building.
- The developed metric is a multi-phase metric. Unlike most existing metrics, it can quantify resilience during and after the disturbance.
- The boundaries of thermal resilience evaluation with the developed metric are within the building characteristics (including building envelope and systems) and occupancy of the building. Therefore, the difference created in thermal resilience due to the building characteristics and occupancy can be captured by the developed metric.
- The results of the case study building show a significant influence from the building upgrade from a standard to passive design on the building's thermal resilience against a power failure in winter. This result was expected from the performance of standard and passive designs, but the resilience quantification can be more insightful for resilience comparison of competitive designs or resilience enhancement strategies
- The implementation of the battery storage and PV systems as resilience enhancement strategies can improve resilience level for the considered case study in the range of 9–22 degree.hours and 20–50 degree.hours, respectively.
- A less resilient design (e.g. standard design) will gain more significant improvements in the WUMTP when equipped with the resilience enhancement strategies.

The application of resilience quantification and labelling methods that are analysed in this paper can be an effective step for building designers and decision-makers to design resilient buildings to be prepared for, absorb the impact of, adapt to and recover from disruptive events. Incorporating thermal resilience labels in the design, planning and operation phases of existing and newly-built buildings and including them in the energy performance certificates (EPCs) can be valuable. This information can provide a better understanding of the building performance under disruptive events and facilitate a design selection that not only performs well under design conditions but also it is a safe design for upcoming uncertainties and changes in the future.

Declaration of competing interest

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

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