Assessment of passive and active buildings resilience to gas supply disruption in winter across European climates

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Abstract

The energy performance of buildings is strongly influenced by several foreseeable and unforeseeable events during the operation phase, including natural hazards or energy supply disruptions. The increase of these events has raised attention on resilience, identified as the capability of buildings to react to such events guaranteeing the continuation of their operations.

This paper investigates the resilience of residential reference buildings sited in different European climates (Athens, Berlin, Madrid, Turin, Stockholm). It simulates an eventual disruption of gas supply during winter carrying out energy dynamic simulations. Proposing new metrics to assess the building resilience, this paper quantifies the passive and active resilience of the main building components, both envelope and HVAC systems. It also analyses the effect of retrofit interventions on building resilience depending on climate. Results enlighten possible emergency interventions with backup electricity solutions to be activated to guarantee minimum services during the disruptive event associated with climate or geopolitical issues. The importance of increasing self-sufficiency in buildings through renewable energy sources is emphasized to favour the continuation of services in case of energy supply interruption. Finally, the link with energy security and independence is outlined together with possible strategies to increase the building stock resilience in Europe.

Keywords: Building resilience; gas supply disruption; energy independence; climate change; backup solutions; energy crisis.

1. Introduction

Decarbonising the building sector is a global priority of several governments' policies and climate mitigation measures. At European level, the Green Deal aims to cut down the EU's GHG emissions to 55% by 2030 and realize carbon neutrality by 2050 (European Commission, 2019). Furthermore, as stated in the EU “Save Energy”, the need to shorten gas imports and electrify the energy demand make it essential to unlock new available areas to boost renewable energy production (European Commission, 2022a). Increasing energy efficiency by the end of this decade is expected to provide additional benefits, such as higher energy security and lower GHG emissions, delivering a structural reduction in energy use. The REPowerEU Plan set the proposal to raise the renewable energy target to 45%, while the Renovation Wave Strategy point to the need to build and renovate in an energy and resource efficient way (European Commission, 2022b; European Commission, 2020). Accordingly, more ambitious concepts of new buildings as well as deep renovation for existing buildings are needed as pointed out in the recently revision of the EPBD, released at the end of 2021 (EPBD, 2021). Seen as an essential legislative tool to support the implementation of the EU strategy, the EPBD revision set out how the EU can achieve a zero-carbon buildings stock by 2050. It upgrades the existing regulatory framework to reflect higher ambitions and more pressing actions in climate, energy, and social fields. In the light of recent geopolitical events, increasing the EU’s resilience and energy independence from fossil fuel imports has become a priority.

However, despite the efforts to accelerate the decarbonisation process, the worsening of climate change phenomena has stressed the need for pursuing adaptation strategies, aiming to “anticipating the adverse effects of climate change and taking appropriate action to prevent or minimize the damage they can cause or taking advantage of opportunities that may arise” (EEA, 2022). Within its new Adaptation Strategy, the European Commission has proposed its ambition of adapting to the unavoidable impacts of climate change (European Commission, 2021). These considerations, affecting the whole economy, must be further tailored for the building sector. Indeed, building performance, in terms of energy needs and occupants’ comfort, can be influenced by several foreseeable and unforeseeable events during the operation phase. Among them: natural disruptive events (e.g., floods, earthquakes, hurricanes, heat waves, etc.), power outages (because of natural events and/or power grids intermittency), pandemics and new needs (e.g., occupants’ habits, new technologies, new policies or geopolitical changes, etc.) (Homaei et al., 2021). Moreover, given the frequency and intensity of natural hazards, linked to a changing climate, the need for buildings to be able to react to such events and to maintain their operations has become essential. As a consequence, the interest around the concept of building resilience raised (Homaei et al., 2021). Despite the importance and the urgency of this topic, which is strongly intertwined with energy security considerations, there is still a literature gap in terms of metrics capable of quantifying building resilience. Thus, this paper aims to fill this gap in exploring and proposing new metrics for resilience quantification and benchmarking, and exemplifying them for European residential buildings.

However, a first step is the clarification of the concept of resilience in buildings. Indeed, the definition of resilience is not straightforward and has been subject to debates around the meaning and the distinction with other concepts, such as building robustness. Accordingly, the following section summarises relevant resilience definitions in relation to the building sector.

1.1 Overview of resilience definitions

Several resilience definitions are present in the literature, depending on the sector. Resilience has initially been defined in the ecological field as "the ability of an ecosystem to rearrange its organization outside of its equilibrium state to another one when facing a perturbation" (Holling, 1973). In other fields, as engineering and economics, resilience is defined as "the ability of a system to resist perturbations outside of its equilibrium state and its speed to come back to it" (Holling, 1973; Martin et al., 2015). Karamouz et al. (2017) generally define resilience as a system capability to cope with change and maintain its operation, highlighting the similarity among the definitions in different fields. Similarly, Cerè et al. (2017) suggest that resilience can be expressed as "a system readiness in reacting towards disruptive events" and authors well describe how such events could be classified as external or systemic, depending on "their origin in relation to the system". Borrowing the definitions from the other disciplines, the resilience concept has been transferred to the built environment. Moazami et al. (2019) defined resilience as "the capacity of a system to withstand and recover during and after the occurrence of an extreme event", while Sun et al. (2020) propose it as "the ability of a building to prepare for, withstand, recover rapidly from, and adapt to major disruptions due to extreme weather conditions". Moreover, Hewitt et al. (2019) launch a definition of resilience in terms of "availability of services that a building is capable of maintaining under conditions of stress, and its ability to restore those services in order to continue operating". The authors describe that a building should guarantee occupants' needs also in case of a crisis, and, therefore, they identify resilience as "the capacity of a building to sustain atypical operating conditions in disaster situations, rather than succumbing to building failure" (Hewitt et al., 2019).

Some studies refer to the concept of thermal resilience, focusing on building thermal performance during and after a specific disruptive event, aiming to analyse the impact of such events on indoor thermal conditions and, thus, on occupants' comfort and wellbeing (Sun et al. 2020; Homaei et al., 2021). Given the duration of the disruptive events (e.g., violent natural hazards, energy supply disruptions, etc.), the analyses are usually performed over a short time frame (i.e., some days), exploring a building response during and after the disruption occurrence (Homaei et al., 2021). In line with this, the authors defined a resilient building as "able to prepare in the initial state, absorb and adapt during the disruptive event and recover after the disruptive event" (Homaei et al., 2021). Due to the increase of climate change-related disruptions, it is fundamental to understand how buildings could increase their resilience. Cerè et al. (2017) express how climate change can affect all building components (i.e., envelope, systems, and people), in addition to energy consumption and greenhouse gas emissions. In this regard, Osman et al. (2019) suggest that passive strategies can contribute to buildings resilience, optimizing thermal comfort conditions and reducing the dependency on external systems. Moreover, the studies of Sun et al. (2020) and Homaei et al. (2021) aim to evaluate how passive and active energy efficiency measures can improve thermal resilience, to ensure occupant thermal comfort even in case of extreme occurrences. They suggested how building design and retrofit should be accompanied by the coupling of energy efficiency and sustainability considerations with resilience-related ones.

Furthermore, it is fundamental to highlight that building resilience is strongly related to supply networks resilience, since most existing buildings are "highly dependent on outside resources and infrastructure for providing end-use services to occupants" (Hewitt et al., 2019). Within this context, the installation of on-site renewable energy sources (mainly photovoltaic system) and storage systems becomes essential to increase building self-sufficiency.

Building performance tools are typically used to assess resilience in the built environment (Bucking et al., 2022). Homaei et al. (2021) well describe how dynamic energy simulations are fundamental to simulate building performances, even in atypical conditions. According to Homaei et al. (2021), resilience metrics should be able to express "how far and for how long" the performances of a building deviate from normal conditions, and the quantification of resilience features should not be restricted to the occurrence of a disruptive event, but should consider also what happens after the event. An effort is requested to develop consistent and easy-to-use metrics for benchmarking purposes (Homaei et al., 2021), as well as for comparing different buildings (with different dimensions, uses, and locations) (D'Agostino et al, 2022). Despite many authors state the importance of resilience quantification (Homaei et al., 2020), there is an open debate on possible indicators to be used for resilience evaluation (Bucking et al., 2022).

1.2 Research aims

This paper covers the targeted research need of quantifying building thermal resilience to be associated with typical annual indicators (highlighted by Homaei's studies). It aims to propose new indicators to assess thermal resilience and align them with existing indicators used for sustainability and energy performance assessment of buildings. The proposed methodological approach is exemplified carrying out energy dynamic simulations. Reference residential buildings are considered as located in diverse European climatic zones to highlight possible differences arising from climate considerations. In line with recent geopolitical events, the paper simulates an eventual disruption of gas supply during winter. The research aims, on the one side, to quantify the thermal resilience of building components (both envelope and HVAC systems), and, on the other side, to simulate possible emergency interventions to be activated to help occupants in maintaining minimum services during the disruptive event occurrence.

This paper is structured as follows. The methodological approach is reported in section 2, while section 3 describes the applicative study developed and section 4 discusses the main results. Finally, the main conclusive remarks and possible future perspectives are reported in section 5.

2. Materials and methods

The methodological framework developed in this paper to assess and quantify thermal resilience in buildings is reported in Figure 1.

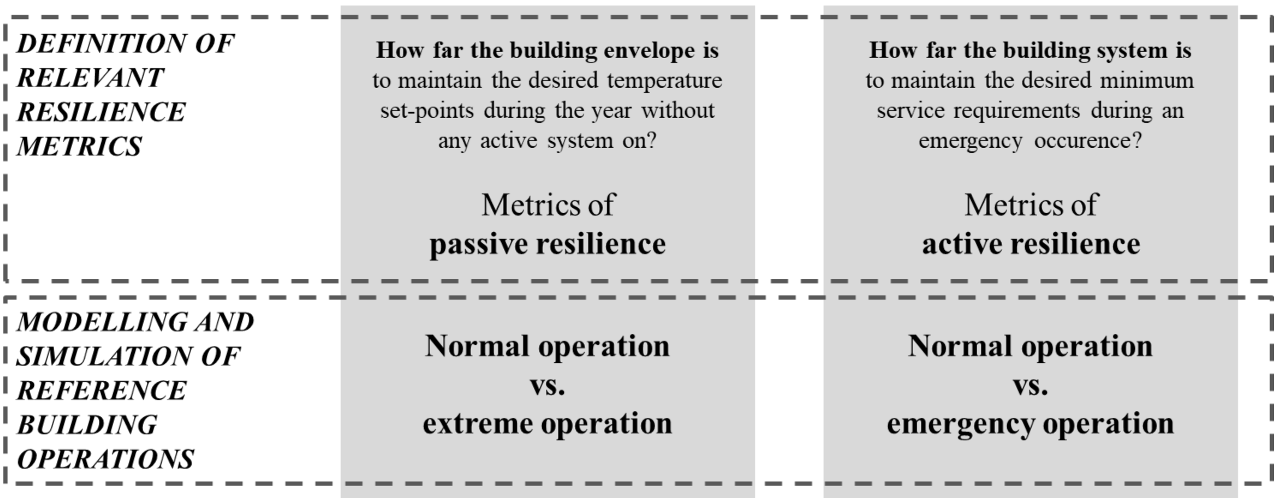

Figure 1 – Methodological framework for resilience assessment.

Resilience assessment and quantification is based on two approaches, supported by the modelling and simulation of specific operations of the reference building under analysis. The first approach develops metrics of passive resilience to estimate the performance of the building envelope and its capability in maintaining the desired indoor air temperature set-points during a whole year. This includes both heating and cooling seasons, as well as the absence of HVAC systems in providing space heating and cooling services.

The other approach develops metrics of active resilience to assess the capacity of the building systems (including eventual backup integrative solutions) in maintaining the desired minimum requirements of heating, cooling and domestic hot water (DHW) services during an emergency event (i.e., gas supply disruption during a short timeframe in winter). To this purpose, as specified in Figure 1, specific building operation conditions (normal and extreme) are assessed through energy dynamic simulations using the EnergyPlus tool.

2.1 Passive resilience metrics

Passive resilience metrics are defined starting from the well-known definition of heating degree days (HDD) and cooling degree days (CDD) for a specific location. These are calculated based on measurements of the outside air temperature to quantify the energy demand of a building in that location. However, besides the location climate, the heating and cooling demand depends on other factors, not considered in the HDD/CDD computations, including the envelope performance and the contribution of solar radiation and internal gains (e.g., occupants, lights, and electric equipment). To overcome these limitations, this paper aims to define proper metrics capable of assessing the capacity of a building envelope to maintain the desired internal temperature during the heating and cooling seasons. In other words, the passive metrics intend to estimate the distance between the desired temperature (set-point) and the indoor air temperature, in turn affected not only by outdoor climate conditions, but also by envelope characteristics, and solar and internal gains. With this purpose, two indicators are defined: the building heating degree days ($HDD_{building}$) and the building cooling degree days ($CDD_{building}$). $HDD_{building}$ is calculated as the sum of the positive differences between the indoor temperature set-point during heating season and the average daily indoor temperature, as reported in Eq. (1):

$$HDD_{building} = \left[\sum_{i=1}^{N_H} T_{setpoint,H} - T_{i,m,daily}\right] if \left(T_{setpoint,H} - T_{i,m,daily}\right) > 0 \quad (1)$$

where $T_{i,m,daily}$ is the mean daily indoor temperature, $T_{setpoint,H}$ is the setpoint temperature during the heating season (20°C), and N_H is the number of days of the heating season. The $HDD_{building}$ indicator includes only days in which the simulated indoor air temperature is lower than the desired set-point temperature.

Conversely, $CDD_{building}$ is calculated as the sum of the positive differences between the average daily indoor temperature and the temperature set-point during cooling season, as shown in Eq. (2):

$$CDD_{building} = \left[\sum_{i=1}^{N_C} T_{i,m,daily} - T_{setpoint,C}\right] if \ (T_{i,m,daily} - T_{setpoint,C}) > 0 \quad (2)$$

where $T_{setpoint,C}$ is the setpoint temperature during the cooling season (26°C), and N_C is the number of days of the cooling season. In this case, only days with simulated indoor air temperatures higher than set-point are considered.

By definition, the higher the building degree days (both heating and cooling), the lower the building envelope performance is. This computation can be used to estimate the effect that envelope retrofit interventions may have in reducing the building degree days, with respect to the current status. The computation of the passive metrics is performed to compare two building operation conditions: normal and extreme. The former is used to simulate normal building operations, with HVAC systems working to maintain fixed set-points during heating and cooling seasons. The latter, performing free-running simulations, models an extreme condition in which HVAC systems are absent. This allows to evaluate the indoor temperature evolution as a function of external climate conditions, envelope characteristics and internal assumptions.

2.2 Active resilience metrics

Moving to active resilience, this paper aims to evaluate how a building might respond to the occurrence of an unforeseeable event. This is done through the deployment of emergency interventions allowing to provide minimum services of heating, cooling and DHW production to occupants, with backup solutions, potentially powered by renewable energy sources. A metric of equivalent photovoltaic (PV) surface is calculated, to estimate the additional amount of surface to be covered by PV panels producing over a year the electricity needed to meet the surplus consumed by the backup systems during the emergency period. To this purpose, the normal operation conditions of the building are compared with the emergency conditions, in which a set of backup integrative solutions are activated to maintain acceptable conditions to occupants. The emergency conditions include the identification of minimum acceptable requirements in terms of indoor temperature set-points to be guaranteed during the emergency occurrence.

3. Resilience metrics application

3.1 Reference building model in normal operation

The dynamic simulation tool EnergyPlus (version 9.4) is used for modelling the reference building and assessing its resilience. EnergyPlus is a modular building energy analysis and thermal load simulation program, developed by the research laboratories of the U.S. Department of Energy since 2001. It was chosen for the aim of this study for being an open-source free software, well-known and widely used all over the world, in both academic and commercial contexts, for building and HVAC system design and dynamic simulation. Among all simulation tools, EnergyPlus is not an user-friendly software, but it is so far one of the most used for being one of the most mature ones in terms of capabilities (Crawley et al., 2008).

The methodological approach is applied to a single-family house (SFH), built in the 70s and located in different European climatic zones. The SFH is modelled to be representative of a wider portion of the European building stock. As shown in Figure 2, it is a two-storey building, with a net conditioned area of almost 190 m^2. The ground floor is constituted by two unconditioned spaces (i.e., a garage and a storage room) and five conditioned spaces (i.e., kitchen, living room, bathroom, bedroom, and a stairwell). Similarly, the first floor presents an additional unconditioned storage room and six conditioned zones (i.e., kitchen, living room, bathroom, two bedrooms and a stairwell). All conditioned rooms are heated and cooled, with the sole exception of bathrooms and stairwells. According to national Standard, air temperature set-points for heating and cooling seasons are set to 20°C and 26°C, respectively, although current recommendations are 19°C in winter and 27°C in summer (International Energy Agency, 2022). The building is assumed to be naturally ventilated, considering a ventilation requirement of 11 l/(s·person) (UNI 10339, 1995). A gas boiler (with nominal efficiency equal to 0.86) is assumed to meet heating loads, exploiting radiators, while a direct expansion system is assumed for space cooling, simulating a typical multi-split air conditioning system. DHW is provided by the gas boiler, whose requirements are defined in accordance with UNI/TS 11300-2 (2004). Regarding internal heat sources due to occupancy, lighting and electric equipment, usage patterns are derived from EN 16798-1 (2019) for single family houses. Specific values of 42.5 m^2/person and 2.4 W/m^2 are used for occupancy and electric equipment, respectively (EN 16798, 2019). The value of power density per unit area from lighting systems is equal to 7 W/m^2, as derived from UNI/TS 11826 (2021).

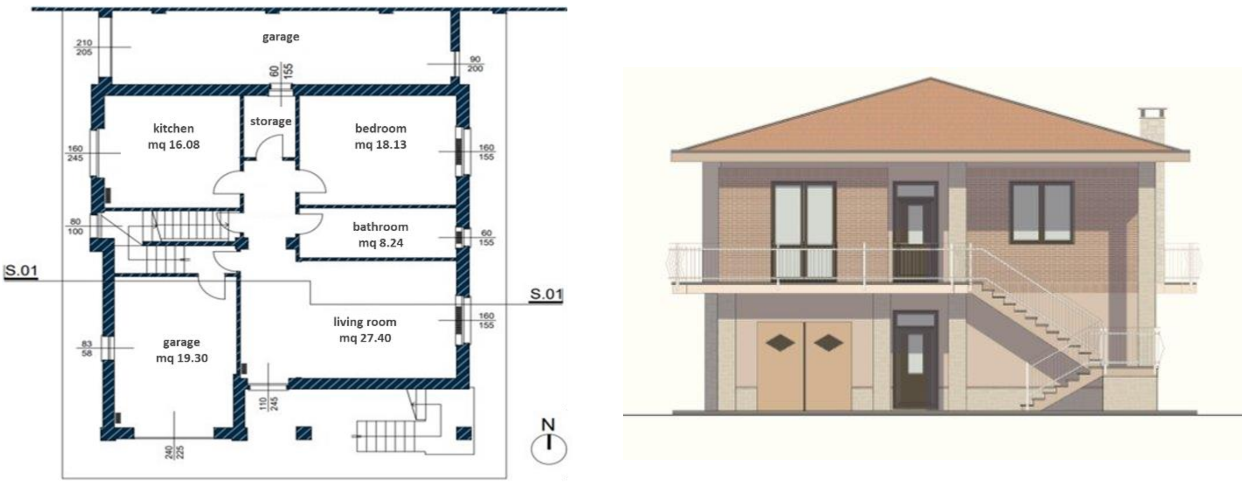

Figure 2 – Ground floor and south-oriented façade.

To account for the effect of climate on the energy behaviour of the building under investigation, the SFH is modelled in five different locations chosen as representative of the five European climatic areas identified in (Hermelink et al., 2013). In more details, Athens and Madrid are selected for the Mediterranean zones 1 and 2, Turin for the Continental zone 3, Berlin for the Oceanic zone 4 and Stockholm for the Nordic zone 5. The duration of the heating season is assumed from the European project Typology for Building stock energy Assessment (Ballarini et al., 2014; TABULA webtool), while the cooling season is always assumed as complementary to the heating one (Table 1).

Table 1 – Heating season for the different EU locations.

Building location	*Heating season*
Athens	December 2nd – March 15th
Madrid	November 1st – April 15th
Turin	October 15th – April 15th
Berlin	September 21st – April 30th
Stockholm	September 9th – May 25th

For all locations, DOE Weather for Energy Calculation Database of Climatic Data is deployed, using IWEC weather files. These files are derived from up to 18 years (1982-1999 for most stations) of DATSAV3 hourly weather data originally archived at the U. S. National Climatic Data Center.

Construction typologies for the SFH in the diverse climatic zones and associated U-values are defined based on the EU TABULA project outcomes (TABULA webtool). TABULA project created a harmonised structure for European building typologies in order to estimate the energy demand of residential building stocks at national level and, consequently, to predict the potential impact of energy efficiency measures and to select effective strategies for upgrading existing buildings. Moreover, to assess the impact of envelope retrofit interventions on buildings resilience, the models are replicated to assume the substitution of existing windows with more efficient ones (double or triple glasses depending on the location) and the addition of insulation (with variable thicknesses) on external walls and on the superior ceiling towards the unconditioned attic. According with the perspective of proposing only retrofit interventions that are easy and quickly to be realised without revolutionizing the building, the ground floor is not retrofitted. Indeed, due to the specific structural features of the case study in order to retrofit the ground floor a complete demolition and reconstruction of the slab is necessary. U-values for retrofit interventions are set according to existing regulations in the diverse locations. A summary of the considered U-values of the main construction elements is provided in Table 2.

Table 2 – U-values [kWh/m^{2}K] for the selected locations, pre- and post-retrofit interventions.

		Athens	*Madrid*	*Turin*	*Berlin*	*Stockholm*
Pre-retrofit	External wall	1.67	1.32	1.21	0.98	0.30
	Ground floor	0.91	0.87	1.73	0.74	0.31
	Ceiling	1.43	1.43	1.43	0.50	0.21
	Window	4.7	4.7	4.7	2.8	2.3
Post-retrofit	External wall	0.45	0.42	0.28	0.21	0.13
	Ground floor*	0.91	0.87	1.73	0.74	0.31
	Ceiling	0.36	0.31	0.23	0.15	0.13
	Window	1.9	1.8	1.4	1.0	1.2

** the ground floor is not retrofitted in this application*

Due to a recently substitution of the gas boiler, retrofit interventions are applied only to the building envelope leaving HVAC and DHW production systems unchanged.

3.2 Emergency operations

This paper assesses the SFH thermal resilience in case of gas supply disruption during the week between 23rd and 29th January, impacting space heating and DHW services provided by the existing gas boiler. To cope with the emergency, a set of backup integrative systems to be activated in case of emergency and supplied by electricity are considered. Specifically, being the SFH already equipped with a direct expansion system for space cooling, the same HVAC system is assumed to be activated in case of emergency (i.e., 2 days after the energy supply interruption) to provide space heating. In case of heating service disruption, the indoor temperature values appear to be higher at ground floor with respect to the first floor, and, thus, during the emergency, inhabitants are assumed to occupy only a limited number of zones on the ground floor (i.e., kitchen, bathroom, living room and bedroom). Simulating emergency minimum requirements, heating temperature set-points for kitchen, bedroom and living room at the ground floor are set equal to 17°C, in line with thermal comfort minimum requirements reported in (EN 16798-1, 2019). Occupancy, lighting, and equipment profiles are updated for distinguishing between occupied and non-occupied zones. Finally, an electric boiler (with 0.95 efficiency) is assumed to be installed for producing DHW during the emergency period.

4. Results and discussion

4.1 Passive resilience: the case of Turin

Results are first shown for the assessment of the SFH passive resilience, comparing normal operations with extreme ones (i.e., free running simulations, assuming no HVAC systems for space heating and cooling services). The application is proposed for the SFH in Turin, which presents an average climate among the analysed locations. Figure 3 shows the trend of the daily mean indoor air temperature over an entire year of simulation, considering pre-retrofit (solid lines) and post-retrofit (dotted lines) conditions, for both normal (orange) and extreme (blue) operations. The black solid lines indicate the duration of heating and cooling seasons.

In normal operations, the retrofit intervention guarantees a lower oscillation of indoor air temperature during mid seasons, when internal conditions are shaped by external climate and no HVAC system is activated. Moreover, Figure 3 shows the impact of retrofit interventions in case of extreme operation, showing how temperatures are slightly higher during the heating season with respect to pre-retrofit situation.

Figure 4 reports the evolution of the daily mean indoor air temperature in case of emergency operations, in which the only difference with normal conditions occurs during the 23rd – 29th January week. It is worth noting that the graph represents the mean temperature for all conditioned zones, thus explaining why temperatures are lower than the fixed emergency set-point of 17°C (set-point condition only for the zones heated during the emergency week, i.e., bedroom, kitchen and living room at ground floor). It is also interesting to note how, also in this case, the effect of retrofit is visible, inducing a lower decrease of internal temperatures during the emergency period.

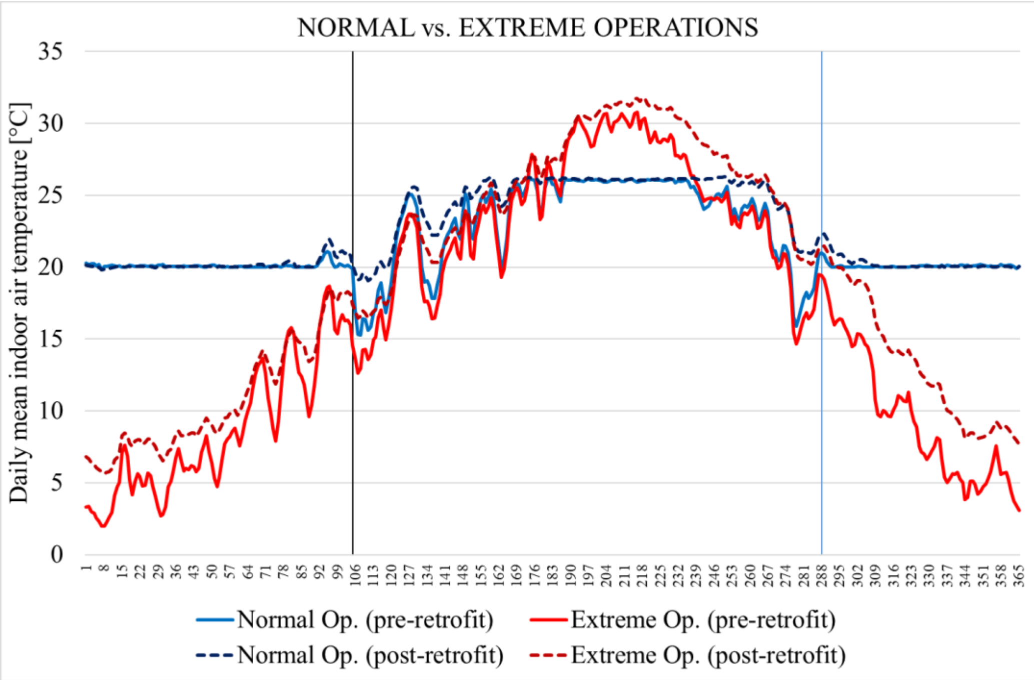

Figure 3 – Daily mean indoor air temperature for the SFH located in Turin for normal and extreme operations, pre-retrofit (dotted lines) and post-retrofit (solid lines).

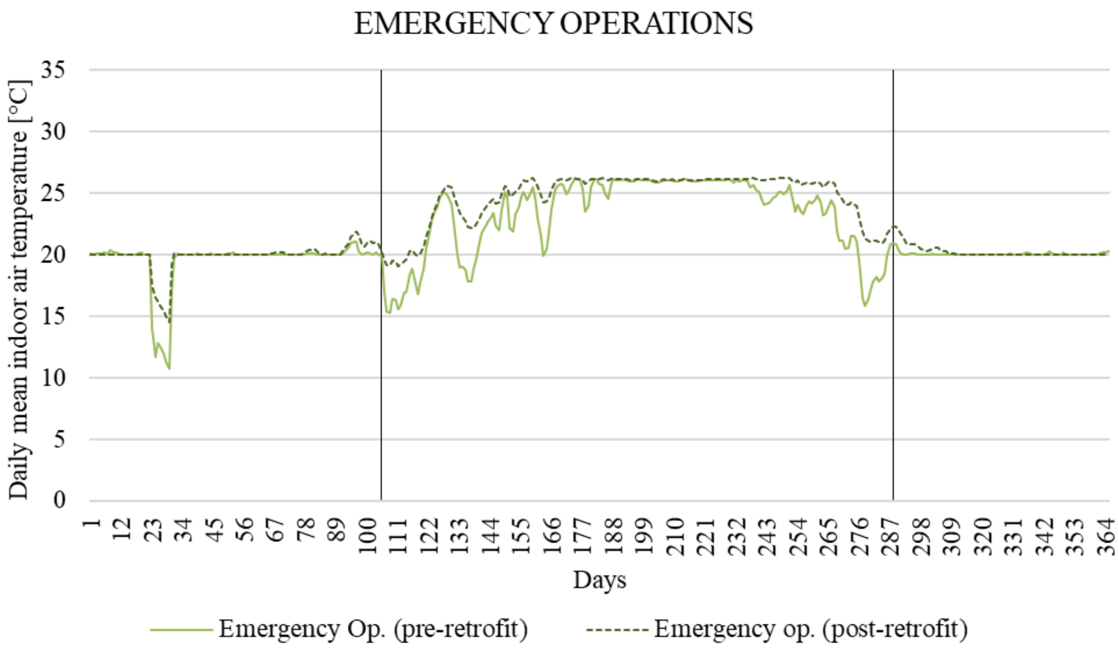

Figure 4 – Daily mean indoor air temperature for the SFH located in Turin for emergency operations, pre-retrofit (dotted lines) and post-retrofit (solid lines).

The detail of the indoor air temperature variation within the different thermal zones during the 23rd – 29th January week is exemplified in Figure 5 for the SFH located in Turin, in pre-retrofit conditions. The graph also presents the variation during the weeks before and after the gas supply disruption. As previously mentioned, the backup option for space heating (i.e., direct expansion system) is activated after two days of emergency, during which the graph shows the decrease of the indoor air temperature in all zones. Then, the splits are activated for F0_bedroom, F0_livingroom and F0_kitchen, where the temperature increases. When gas supply is restored, the figure well reports the needed time for all zones for returning to normal conditions (approximately 2 days).

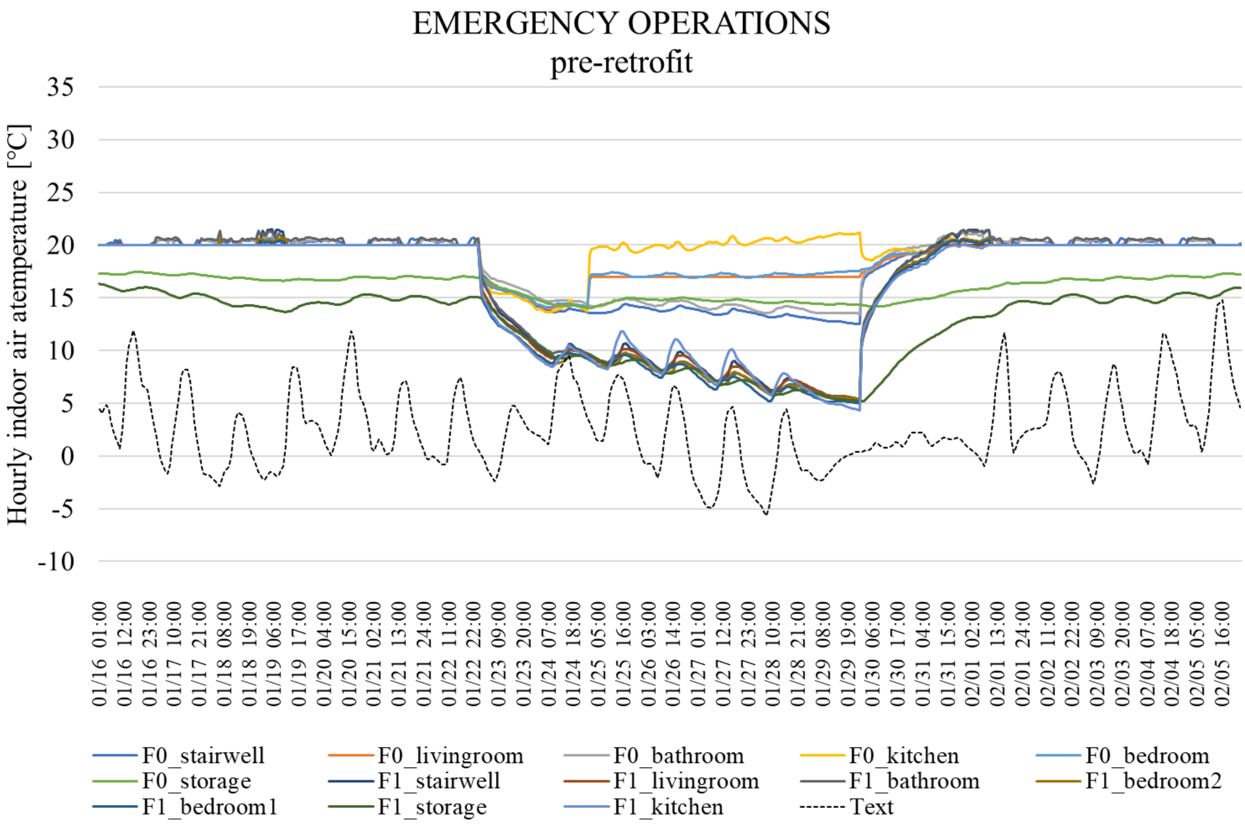

Figure 5 – Hourly external temperature and thermal zones indoor air temperature variation for the SFH located in Turin for emergency operations, pre-retrofit. F0 = ground floor; F1 = first floor.

Based on the methodological framework proposed in section 2, building heating and cooling degree days are computed for the SFH in normal, extreme, and emergency operations. The outcomes for the SFH located in Turin, for both pre- and post-retrofit conditions, are shown in Table 3.

Table 3 – Summary of $HDD_{building}$ and $CDD_{building}$ for SFH located in Turin in normal, extreme, and emergency operations conditions.

		$HDD_{building}$ [°C days]			$CDD_{building}$ [°C days]		
		Ground floor	First floor	Entire building	Ground floor	First floor	Entire building
pre-retrofit	*Normal op.*	0.4	0.3	0.3	1.1	6.1	3.2
	Extreme op.	1,979.8	2,042.0	2,013.8	140.8	199.6	172.4
	Emergency op.	26.3	84.6	58.2	1.4	6.1	3.5
post-retrofit	*Normal op.*	0.6	0.7	0.6	5.9	20.2	12.0
	Extreme op.	1,508.8	1,475.9	1,490.7	240.3	348.3	297.1
	Emergency op.	18.7	38.9	29.8	5.9	20.2	12.0

The first significant result comes from the comparison between normal and extreme operations, for both envelope characteristics (pre- and post-retrofit). $HDD_{building}$ values are approximately null for normal operations, meaning that during the heating season the HVAC system is able to meet fixed internal set-points, compensating thermal losses due to ventilation and transmission through the envelope. However, the results greatly change when HVAC systems are not activated, showing the inefficacy of the building envelope to maintain acceptable indoor conditions during both heating and cooling seasons. It is interesting to note how the ground floor (thanks to the direct contact with the ground) has a slightly better behaviour than the first floor, which is more sensible to external air temperature variations in both heating and cooling seasons. Furthermore, comparing the extreme operations in pre- and post-retrofit conditions, it can be noted how the $HDD_{building}$ values decrease when the envelope performances are increased through retrofit interventions. This confirms how the building degree days (both heating and cooling) and the envelope performance are inversely related. For the cooling season, an opposite result is noticeable, with $CDD_{building}$ values increasing after the retrofit interventions, which could probably increase overheating occurrences.

Another relevant outcome is associated to the $HDD_{building}$ results during the emergency operations. This shows higher values than the normal operations, due to the lower mean air temperatures during the week of gas supply interruption. As already pointed out, the $HDD_{building}$ values decrease in case of retrofit interventions, in line with the results of Figure 4. Within normal operations, the

$HDD_{building}$ results for the ground and first floors are comparable; while in case of emergency conditions the building experiences more differences. However, this result is influenced by the assumption of heating only a limited zones of the ground floor (where $HDD_{building}$ values are lower), not occupying the first floor.

4.2 Active resilience: the comparison between different European climates

In this section, results are shown for the assessment of the SFH active resilience, giving insights for the analysed European locations: Athens, Madrid, Turin, Berlin, and Stockholm, covering the main European climatic variability. Starting from normal operations, the results obtained from the hourly-based simulations in terms of annual final energy consumptions are summarized in Figure 6.

The simulated energy consumption appears strongly influenced by the external climate across the different locations, as well as by the envelope characteristics, in both pre- and post-retrofit conditions. Indeed, the gas consumption increases moving from Athens to Berlin due to climatic conditions becoming more rigid during the heating season. Otherwise, it can be noted how the gas consumption in Stockholm is lower as influenced by the high performance of the SFH envelope already in force in the current status (see Table). Strong gas consumption reductions are obtained thanks to retrofit interventions on external walls and superior ceiling, with Turin and Berlin experiencing the higher contractions. As regards electricity consumption (for space cooling, fans and pumps, and lights and electrical equipment), the results are more stable, and gradually decrease with retrofit interventions in all locations.

The results of Figure 6 are compared with the final energy consumption obtained simulating the emergency operations (i.e., interruption of gas supply in the week 23rd - 29th of January and associated activation of backup systems for guaranteeing the continuation of heating and DHW minimum services to occupants), as shown in Figure 7.

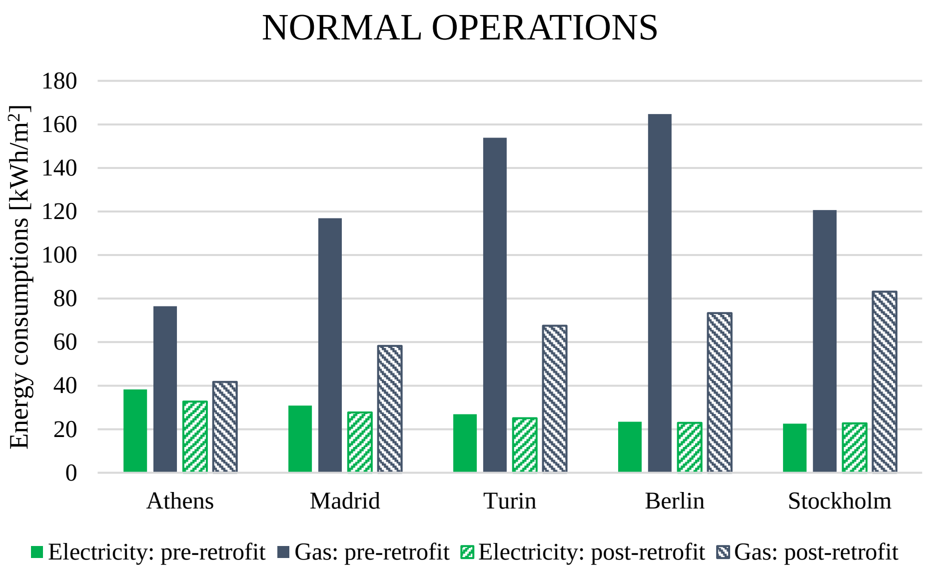

Figure 6 – Simulated electricity and gas consumptions for the five European locations in normal operation, pre- and post-retrofit interventions.

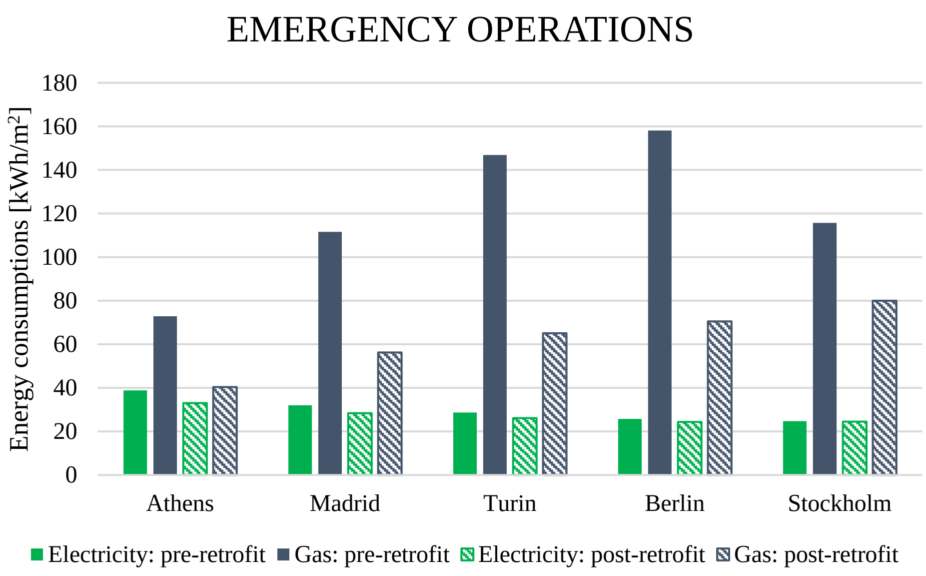

Figure 7 – Simulated electricity and gas consumptions for the five European locations in emergency operation, pre- and post-retrofit interventions.

Comparing Figure 6 with Figure 7, in all locations, the model results experience a reduction of gas consumption in the emergency conditions with respect to normal operations, and a consequent increase of electricity consumption. This is a consequence of the activation of the integrative electricity-fuelled backup systems (i.e., direct expansion system for space heating and electric boiler for DHW production), to tackle the interruption of gas supply during the emergency. The electricity surplus depends on the location, and increases passing from Athens (hot climate) to Stockholm (cold climate). Moreover, the extra-consumption is lower in the post-retrofit models, in which the buildings are more passive resilient to the emergency occurrence and the indoor temperature decreases in a more controlled way, thus requiring a lower integration through electricity-fuelled options (as discussed for Turin SFH in section 4.1).

These considerations are well highlighted in Figure 8 and Figure 9, presenting the breakdown of the needed electricity surplus during the emergency period. This is shown separating the consumption of the electric boiler for DHW production from all other variations of electricity consumption, including the activation of the direct expansion system for space heating and the variation of lighting systems and electrical equipment usage, due to the schedule modification (as reported in section 3.2).

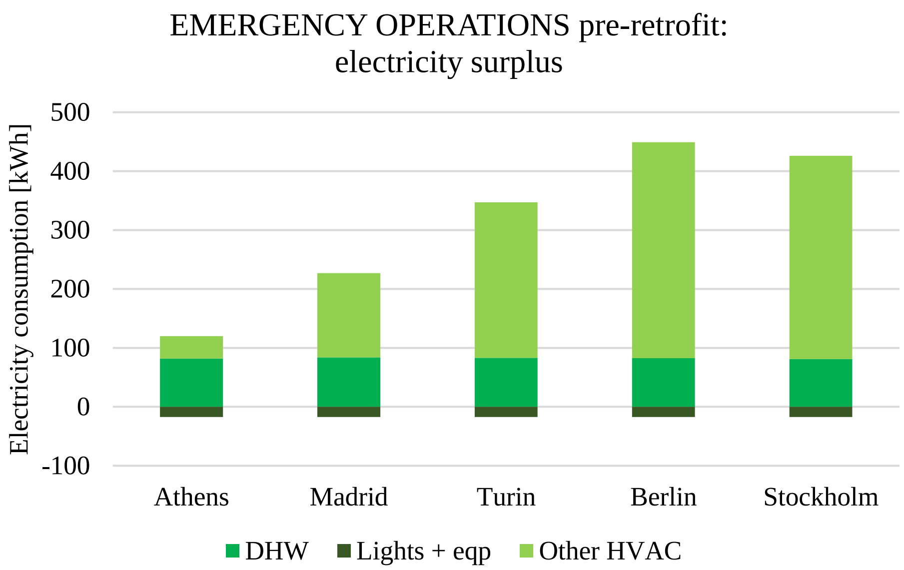

Figure 8 – Breakdown of electricity surplus during the emergency period for the five European locations, pre-retrofit.

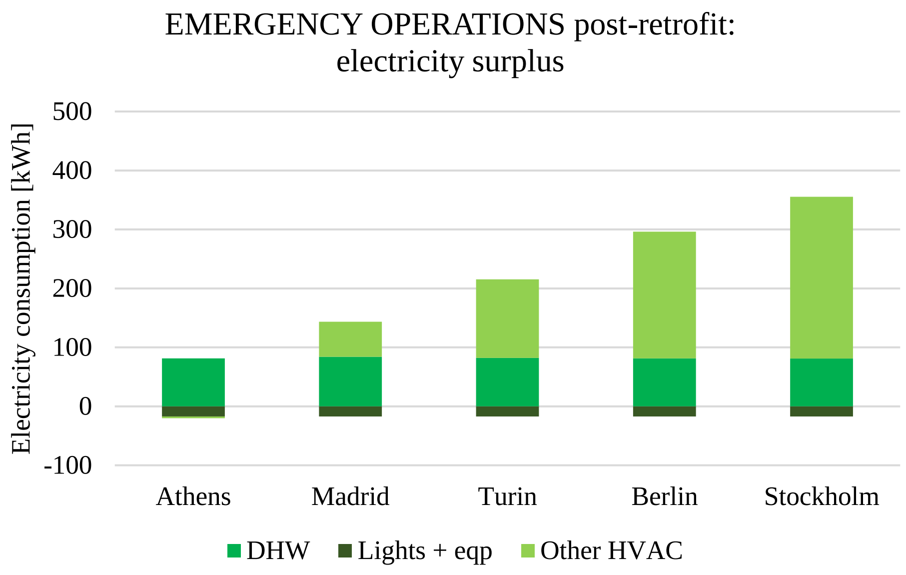

Figure 9 – Breakdown of electricity surplus during the emergency period for the five European locations, post-retrofit.

As expected, the electricity consumed by the backup boiler for DHW production is constant in all locations (same water supply temperature and same water need) and not dependent on retrofit conditions. The same is for the reduction of electricity consumption due to a lower usage of lighting systems and electrical equipment in the non-occupied zones during the emergency week (these values are not dependent on external conditions, but only on the predefined usage profiles). Instead, it is interesting to compare the electricity surplus due to the HVAC system usage in the different European locations, seeing the gradual increment of this quota concurrently with outdoor climate tightening during the heating season (the behaviour of the SFH in Stockholm in pre-retrofit conditions has been discussed previously). Moreover, the breakdown well shows the effect of retrofit interventions in reducing this electricity surplus already shown in Figure 7. In this context, the case of Athens is particularly interesting, showing how, thanks to the retrofit of the envelope, the passive resilience would be sufficient to guarantee acceptable indoor conditions to occupants, even without the activation of the backup system for space heating.

Finally, to provide an easy-to-use metric of active resilience, the annual electricity consumption of the SFHs in normal and emergency operations is translated into an indication of the PV surface needed to meet it. Figure 10 shows the PV surface requested to match the electricity additional demand in the different locations comparing normal and emergency operations. In detail, PV system is simulated as integrated in the South-oriented building pitch; this represents the optimized orientation for all the analysed locations. Panels inclination is optimized in function of the location (in a range from 31° of Athens to 44° of Stockholm). The system is sized (in terms of kW_{peak}) in order to cover the annual electricity consumption of the house in normal operation and in emergency one. Then, the equivalent surface for the two sizes is calculated. The additional PV surface is calculated subtracting the panels area needed in normal operation to the area needed in emergency operation. The results resemble the outcomes of Figure 8 and Figure 9, showing how the additional PV surface increases moving from hot (Athens) to cold (Berlin and Stockholm) climates, with values depending also on the envelope performance of the SFHs in both pre- and post-retrofit conditions.

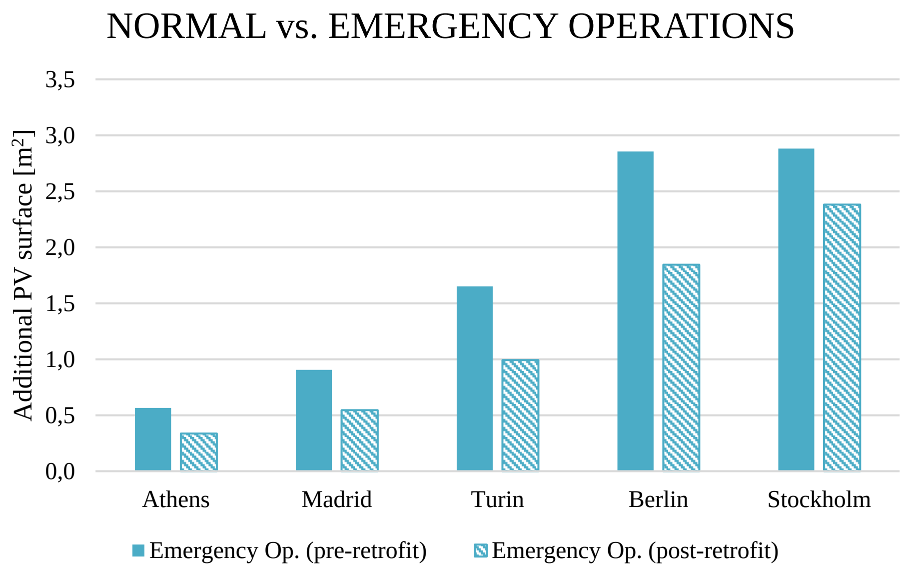

Figure 10 – Additional PV surface needed to meet electricity consumptions in emergency operations w.r.t normal ones, for the five European locations, pre- and post-retrofit interventions.

Renewable energy sources provide positive results increasing building readiness and self-sufficiency over an annual energy balance. However, they cannot guarantee alone the energy independence during the considered winter emergency week, even with storage. Another retrofit intervention, not accounted within this research (as explained in 3.1), could involve the combination of heat pumps and PV to cover the building energy needs. Further research can be devoted towards this direction.

5. Conclusions

EU energy and climate policies are focused in reducing energy consumption, increasing thermal resilience and energy independence from fossil-fuel imports. Recent geopolitical tensions have further drawn the attention on the ability of buildings to stand eventual failures of their functionality during disruptive events and to swiftly recover maintaining minimum services and guaranteeing acceptable indoor conditions to occupants. This paper overcomes a literature gap in terms of easy-to-use metrics able to assess and benchmark buildings thermal resilience. Indeed, it proposes new metrics to quantify passive and active thermal resilience depending on the location and climate. The developed framework is tested in a reference single family house (SFH) located in five diverse European climatic zones.

The analysis of the passive resilience has focused on the envelope performance, which is evaluated through the metrics of building heating and cooling degree days ($HDD_{building}$ and $CDD_{building}$). The modelling of the SFH located in Turin shows the efficacy of the proposed indicators in assessing the envelope intrinsic capability to maintain indoor acceptable conditions in case of inactivation of HVAC systems. Within the framework of this paper, the $HDD_{building}$ metric appears more relevant than $CDD_{building}$, due to the lower space cooling needs of residential buildings. However, authors believe that the $CDD_{building}$ metric would be of significant interest for non-residential buildings, which cooling requirements might be higher than heating ones. This indicator would become more relevant if considering the upcoming increase in outdoor air temperature in all climatic zones, because of climate change, which will profoundly affect buildings behaviour and operations. Future development of the research consists in assessing $HDD_{building}$ and $CDD_{building}$ using in simulation models climatic files that take into account the climate change.

The analysis of active resilience has highlighted the importance of equipping buildings with backup integrative systems to be activated in case of emergency to guarantee minimum services to occupants. The paper also highlights how resilience could be improved through the implementation of both passive and active energy efficiency measures. Indeed, actions to reduce gas consumption are particularly important as savings that can be achieved upstream help in refilling storage and thus reduce the supply risks over winter. Furthermore, decreasing the energy demand reduces fossil fuel imports and avoids possible shortages and consequently curtailment measures with related ensuing economic and social consequences.

Another crucial point relates the increase of self-sufficiency through the adoption of renewable energy sources, allowing the continuation of services also in case of energy supply disruption. The proposed metrics of additional PV surface can support backup systems in case of emergency showing how renewables play a crucial role in the energy transition (the additional PV surface requested to meet an annual balance are lower than 3 m^2).

The research work opens the way to further analyses dealing with the development of composite metrics for thermal resilience assessment, as well as to extend their applications to other reference buildings, including non-residential ones. Given the high variability of disruptive phenomena, not restricted to the heating season, other events could be investigated in future works, including the assessment of electricity supply disruption during the cooling season. Moreover, other retrofit interventions, not accounted within this research (as explained in 3.1), could be tested involving the combination of heat pumps and PV to cover the building energy needs.

This paper illustrates how thermal resilience features are essential to stand a complete failure of buildings functionality during disruptive events, which means a reduced access to end-uses services to occupants and a resulting potential risks for them. Resilient buildings, therefore, do not only have to withstand the unexpected events, but they have to be able to recover to acceptable performance level and continue their services even after the disruptive event occurrence.

Giving the essential elements to move from a theoretical to an empirical resilience assessment, this paper highlights how a holistic approach is undoubtedly needed to assess thermal resilience in the building sector. Indeed, other aspects have to be taken into account in resilience evaluation, like financial performance of the different proposed backup solutions. Due to the urgency of this topic, the results of this paper can provide useful guidance for specific policy initiatives dealing with buildings, energy, and resilience. The developed metrics can be aligned with existing indicators typically used in building energy performance and sustainability. The synergy among these metrics could better connect resilience with linked topics, such as energy safety and flexibility. In the view of the forthcoming energy and climate targets, assessing building resilience is a first step to develop targeted measures and coordinated actions, both preventive and emergency, to increase it. This represents undoubtedly a challenge, but also a unique opportunity to boost energy independence, health and security throughout the European building stock.

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References

- Attia S., Levinson R., Ndongo E., Holzer P., Kazanci O.B., Homaei S., Zhang C., Olesen B.W., Qi D., Hamdy M., Heiselberg P. 2021. Resilient cooling of buildings to protect against heat waves and power outages: Key concepts and definition. Energy and Buildings 239, 110869. DOI: 10.1016/j.enbuild.2021.110869
- Ballarini I., Corgnati S.P., Corrado V. 2014. Use of reference buildings to assess the energy savings potentials of the residential building stock: the experience of TABULA project. Energy Policy 68, 273-284. DOI: 10.1016/j.enpol.2014.01.027

- Bucking S., Rostami M., Reinhart J., St-Jacques M. On modelling of resiliency events using building performance simulation: a multi-objective approach. Journal of Buidling Performance Simulation 15(3), 307-322. DOI: 10.1080/19401493.2022.2044906
- Cerè G., Rexgui Y., Zhao W. 2017. Critical review of existing built environment resilience frameworks: Directions for future research. International Journal of Disaster Risk Reduction 25, 173-189. DOI: 10.1016/j.ijdrr.2017.09.018
- Crawley D.B., Hand J.W., Kummert M., Griffith B.T. 2008. Contrasting the capabilities of building energy performance simulation programs. Building and Environment 43, 661–673. DOI: 10.1016/j.buildenv.2006.10.027
- D’Agostino D., Parker D., Epifani I., Crawley D. and Lawrie L. 2022. How will future climate impact the design and performance of Nearly Zero Energy Buildings (NZEBs)? Energy 240, 122479. DOI: 10.1016/j.energy.2021.122479
- DPR 412/93. Decreto del Presidente della Repubblica 26 agosto 1993, n. 412 Regolamento recante norme per la progettazione, l'installazione, l'esercizio e la manutenzione degli impianti termici degli edifici ai fini del contenimento dei consumi di energia, in attuazione dell'art. 4, comma 4, della legge 9 gennaio 1991, n. 10.
- Ente Nazionale Italiano di Unificazione. 2014. Prestazioni energetiche degli edifici. Parte 2: Determinazione del fabbisogno di energia primaria e dei rendimenti per la climatizzazione invernale, per la produzione di acqua calda sanitaria, per la ventilazione e per l’illuminazione in edifici non residenziali (UNI/TS 11300-2).
- Ente Nazionale Italiano di Unificazione. 2021. Illuminazione di interni residenziali domestici con luce artificiale (UNI/TS 11826).
- European Commission. 2021. Revision of the Directive of the European Parliament and of the Council on the energy performance of buildings (recast), COM(2021) 802 final. Available

at https://ec.europa.eu/energy/sites/default/files/proposal-recast-energy-performance-buildings-directive.pdf

- European Commission, 2022 a. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. EU 'Save Energy', COM(2022) 240 final. available at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52022DC0240&from=EN
- European Commission, 2022b. REPowerEU Plan. COM(2022) 230 final. available at https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483
- European Commission, 2021. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. Forging a climate-resilient Europe – the new EU Strategy on Adaptation to Climate Change. COM(2021) 82 final.
- European Commission, 2020. A Renovation Wave for Europe - greening our buildings, creating jobs, improving, COM(2020) 662 final, available at: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1603122220757&uri=CELEX:52020DC0662.
- European Commission, 2019. Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, the European Green Deal, COM(2019) 640, 11.12.2019, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2019%3A640%3AFIN
- European Committee for Standardization. 2019. Energy performance of buildings – Ventilation for buildings. Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics (EN 16798-1).

- European Environmental Agency (EEA). 2022. What is the difference between adaptation and mitigation? Available at: https://www.eea.europa.eu/help/faq/what-is-the-difference-between Accessed: June 2022.
- Hermelink A., Schimschar S., Boermans T., Pagliano L., Zangheri P., Armani R., Voss K., Musall E., Ecofys, Politecnico di Milano/eERG, University of Wuppertal. 2013. Towards nearly zero-energy buildings. Definition of common principles under the EPBD. Final report (Project number: BESDE10788).
- Hewitt E., Oberg A., Coronado C., Andrews C. 2019. Assessing “green” and “resilient” building features using a purposeful systems approach. Sustainable Cities and Society 48, 101546. DOI: 10.1016/j.scs.2019.101546
- Holling C.S. 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systematics 4, 1–23.
- Homaei S., Hamdy M. 2021. Thermal resilient buildings: How to be quantified? A novel benchmarking framework and labelling metric. Building and Environment 201, 108022. DOI: 10.1016/j.buildenv.2021.108022
- International Energy Agency (IEA). 2022. Playing my part. How to save money, reduce reliance on Russian energy, support Ukraine and help the planet. https://iea.blob.core.windows.net/assets/cbc97c70-8bcf-4376-a8a9-4cd875195f6a/Playingmypart.pdf
- Martin R., Sunley P. 2015. On the notion of regional economic resilience: conceptualization and explanation. Journal of Economic Geography 15 (1), 1–42. DOI: 10.1093/jeg/lbu015
- Moazami A., Carlucci S., Geving S. 2019. Robust and resilient buildings: A framework for defining the protection against climate uncertainty. IOP Conference Series: Materials Science and Engineering 609, 072068. DOI: 10.1088/1757-899X/609/7/072068

- Osman M.M., Sevinc H. 2019. Adaptation of climate-responsive building design strategies and resilience to climate change in the hot/arid region of Khartoum, Sudan. Sustainable Cities and Society 47, 101429. DOI: 10.1016/j.scs.2019.101429
- Sun K., Specian M., Hong T. 2020. Nexus of thermal resilience and energy efficiency in buildings: A case study of a nursing home. Building and Environment 177, 106842. DOI: 10.1016/j.buildenv.2020.106842
- TABULA webtool. Available at: https://webtool.building-typology.eu/#bm Accessed: September 2022