Politecnico di Torino

Master’s Degree course in Energy and Nuclear Engineering

Master’s Degree Thesis

Study of energy savings and environmental and economic impact of resilient cooling technologies in existing buildings

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Abstract

Ecosystems and the built environment are greatly impacted by climate change brought on by human activity. Due to its alterations, local extreme events occur more frequently and more severely, increasing their fatalities and economic costs. The Mediterranean area is particularly affected by heatwaves, which are extremely critical for health and productivity of people inside the dwellings as well as for energy consumptions related to cooling need. These events also increase the chance of power outages, which disable the operation of electrically powered cooling systems, raising the likelihood of indoor overheating. For these reasons, buildings play a crucial part in mitigating the effects of changing climate, in the optic of being resilient to new average conditions and extreme events. Resilience describes the ability of a system to withstand or recover from disruptions, taking advantage from its design and/or adopting appropriate strategies for returning to original conditions in a fast and efficient manner.

This study investigated the resilience of different cooling technologies in the most common construction in Catalan building stock during present and future climatic conditions, heatwaves and power outages, evaluating also their impact on energy consumptions, environment and costs. The techniques implemented in the model include green roof, advanced solar shading, advanced glazing, natural ventilative cooling, vapor compression refrigeration and their combinations. Typical years and heatwaves for the city of Barcelona have been created for three time periods, Present, Mid Future and Long Future. They have been modelled using dynamical downscaled Regional Climate Models, climate projections based on IPCC scenarios. Power outages have been simulated during the most critical scenarios. Resilience was assessed using indicators that take into account climate resistance and thermal comfort. Climate resistance indicators consider the linear correlation between the grade of overheating inside a dwelling and the severity of outdoor conditions. Thermal comfort and survivability indicators evaluate sensations of building's occupants related to several parameters, such as indoor air temperature, operative temperature and relative humidity. A potential scenario for future electric generation was simulated for evaluating the impact of passive measures in the reduction of primary energy use, carbon emissions and costs associated with the use of vapor compression refrigeration.

The original building presented acceptable levels of climate resistance, while thermal comfort conditions resulted poor, especially during heatwaves. The application of the different cooling technologies significantly helped in the improvement of resilience of the dwelling. However, their performances reduced in the future scenarios, especially in the ones presenting severe outdoor conditions. Vapor compression refrigeration resulted the best solution for avoiding overheating inside the apartments, especially in case of heatwaves. Concurrently, natural ventilative cooling achieved good results in the improvement of climate resistance and comfort, as well as in the reduction of cooling and total energy needs of the building. Combinations of several passive measures resulted necessary for maintaining suitable conditions in case of power outages and reducing environmental impact and costs related to the use of vapor compression refrigeration, which confirmed the importance of the building envelope conditions.

Summary

1. Introduction

In the recent years, climate change and its implications on ecosystems and the built environment are becoming an important object of research and discussion in several disciplines and institutions. Fifth Assessment Report (AR5) of Intergovernmental Panel on Climate Change (IPCC) estimates an increase between 0.3 °C and 4.8 °C of global average temperature by the end of the 21st century, compared to the present one (1) (2). These predictions are made considering the continuous increment of temperature during the last century, with an average rate of 0.2 °C per decade (3). There is a strong dependency of these changes with human activities and their consequent emissions of greenhouse gases (GHG) in the atmosphere. From 1992, with the United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro and the following international environmental agreements (IEAs) and frameworks, like the Kyoto protocol of 1997, the international community has been focusing on the reduction of these emissions (4) (5). In 2015, UN Framework Convention on Climate Change (UNFCCC) developers signed the Paris Agreement, with the main objective of limiting global temperature rise below 2 °C above pre-industrial levels and maintaining it below 1.5 °C in the near future (6) (7). Unfortunately, according to the Sixth Assessment Report of IPCC (AR6), actual GHG emissions will lead to a global warming higher than 1.5 °C at the end of the century, reaching this increment in a near term (8).

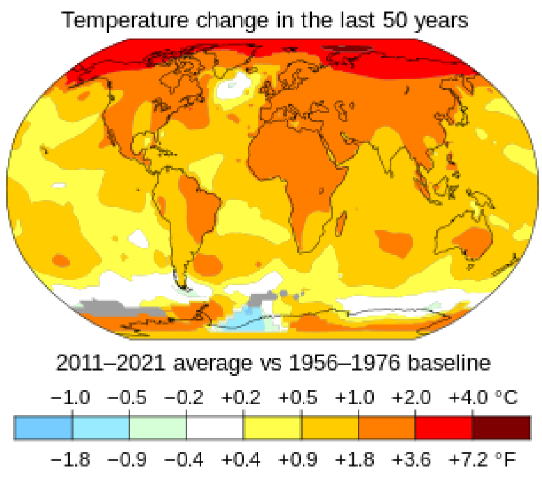


Figure 1: Average surface air temperatures 2011–21 compared to 1956–76 - from (9)

Climate modification would cause the increase in frequency and severity of local extreme events, such as heatwaves, droughts, precipitations, pluvial floods and storms. The annual report of CRED for the year 2022 (10) highlights a slight increase of catastrophic events respect to the period between 2002 and 2021, especially in droughts, floods and wildfires. Increments result much higher comparing the two periods between 1980 and 1999 and 2000 and 2019. In particular, extreme temperatures registered 432 cases instead of the 130 of the previous decades, and floods events increased from 1389 to 3254. These disasters impact considerably on people's health, life and economy. People affected by these events, according to CRED report for the years 2000-2019, passed from 3.25 billion to 4.03 billion and economic losses arrived to 2.97 trillion of US dollars, respect to the 1.63 trillion of the previous decades (11). NOAA (12) evaluated that in the U.S., in almost two decades, extreme events passed from the 6.7 cases per year, with an average of 310 annual deaths and 60 billion dollars annual cost of 2000s period (2000-2009), to the 18.0 cases, 350 deaths and 123.9 billion dollars in the last five years (2018-2022). EMDAT (13) estimated that these events have a high likelihood to be related to climate change, especially heatwaves and storms.

Figure 2: Consequences of climate change – from (14)

For heatwaves, there are several studies on their peaks and occurrence through the years. Many of them show how some events identified in the past as "very rare", now are "unusual", while others considered "impossible" to present are now categorized as "extreme" (15) (16) (17) (18). In the U.S., annual occurrence of heatwaves passed from two events per year in the 1960s to six in the 2010s (19). Group I of AR6 (20) predicted that heatwaves would become much more frequent and severe in case of additional increase of global temperatures. Estimated frequencies are 6 times higher for unusual events and 15 times higher for rare ones respect to pre-industrial scenarios, with an increment of more than 2.5 °C on average daily temperatures of heatwave periods.

Continuous exposure to heat can have a wide range of health implications, like heat strokes, exhaustion, cramps and syncope, that could cause permanent damages and functional impairments (21) (22) (23). In addition, productivity of workers is badly affected by hot periods, increasing the probability of economic losses (24). As a consequence of more frequent and severe heatwaves, deaths and morbidity increased through the last decades and they will continue to follow this trend in the future years. A study of Vicedo-Cabrera et al. (25), regarding effects of climate change on human health, points out how, in the period between 1991 and 2018, 37% of the global heat-related deaths are attributable to anthropogenic climate modification. In 2010 an intense heatwave occurred in Eastern Europe and Western Russia, with temperatures above 30 °C and reaching 40 °C in many major cities, causing approximately 55000 deaths (26). This event, one of the most serious recorded, has a large probability to be caused by human activities, in minor part by urban heat island and largely by greenhouse warming. The analysis of Zhang, G. et al. (27) shows that human-relation to the total heat mortality in China during 1995-2014 is accounted in 17% of the cases. This number would be 1.5 times higher in the next 20 years and 4 times higher by the end of the century, without any effective plan for reducing emissions.

Figure 3: Impact of heatwave on people in the outdoor and indoor environments – from (28) and (29)

Extremely hot outside conditions impact significantly on thermal conditions maintained in the built environment. Heatwave periods could lead to phenomena of overheating inside the building, that affects comfort, productivity and, in some cases, health of occupants. This condition constitutes a serious risk for the population, that spends most of the hours indoor (30). To confirm this, it was evaluated that from the 70000 deaths caused by an extremely severe heatwave in Europe in 2003, 70% of the total occurred indoor (31). Population that is more sensitive to overheating is constituted by old, very young and underlying medical conditions people and pregnant women (32). This is a serious point for countries where a significant part of population is composed by old people, like Europe, that counts 33.6% of citizens over 55 years-old, with an incremental trend for the future (33). Spaces with high internal gains, like offices, or with high insulation, as passive houses, are more exposed to overheating risk, suggesting to consider this aspect in future retrofits and constructions (34) (35).

Warm conditions also impact on the energy consumption of buildings. Almost 40% of the total energy consumption in Europe is imputable to thermal and electric equipment of dwellings (36). Satisfaction of cooling need constitutes the 20% of building electricity consumption, but this number would increase of up to 45% in 2050, according to the report of IEA about the future of cooling (37). This predicted number is justified by the tendency of warmer outdoor conditions and the consequent implementation of vapor compression refrigeration systems, that will be present in almost 2/3 of the global households in the future. There are several studies that confirm the tendency of reduction of heating need and increase of cooling one, directly related to climate change. Berardi and Jafarpur (38) conducted a study for Canadian urban regions, finding an increase of cooling need of 126% and a decrease of heating one of 33%. For Argentinian mid-income houses, Flores-Larsen et al. (39) estimated an increment of 360-790% in cooling and a maximum reduction of 59% in heating need in 2080. Values for cooling may increase in case of heatwave occurrence, accounting up to 50% of the peak demand of buildings during those periods. This would lead to phenomena of overload of electric generators and transmission, that increase GHG emissions per unit of energy produced (40). In addition, extremely hot conditions, especially during nighttime, can stress transmissions, causing their failure and inducing consequential power outages (41). In case of missing electricity, active cooling systems like vapor compression refrigeration results unavailable, increasing the probability of overheating inside the dwellings.

Considering the effect of climate change on health and economy, the built environment must be ready for disruptive occurrences and new climate scenarios. In case of extreme events, buildings should provide a safe and comfortable spaces for their occupants. In this optic, some institutions, like United Nations and IEA, proposed “resilience” as a key component for managing these risks (42) (43). This concept was preliminary defined by Holling (44), describing it as the ability of a system to recover from a shock by first lessening the severity of the disturbance and then adapting its configuration, absorbing the disturbance before significantly changing its structure. In recent years, UN General Assembly Resolution 71/276 defined resilience as: “the ability of a system, community or society exposed to hazards to resist, absorb, accommodate, adapt to, transform and recover from the effects of a hazard in a timely and efficient manner, including through the preservation and restoration of its essential basic structures and functions through risk management.” (42). This definition is strictly correlated to the ones of low-carbon and climate-proof buildings, that provide necessary guidelines for solving root-causes of climate change, protecting from its effects and eventually mitigating them (45).

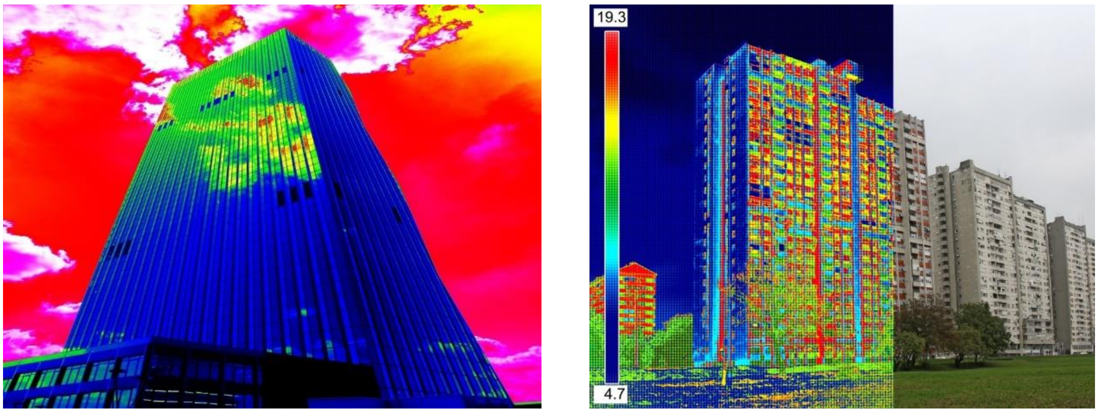


Figure 4: Building Simulation Tool – from (46) and (47)

In order to predict the behavior of buildings to new climate conditions and identifying the technologies that could be assessed as resilient, building performance simulations (BPSs) are essential tools for making this analysis. They are computer-based mathematical models able to consider the dynamic and non-linear processes that govern building performance under real conditions (48) (49) (50). Usually, simulations are conducted using sets of typical months assembled from historical data of

20-30 years (51). However, the review of Herrera et al. (52) highlighted the urgent need of including extreme events, especially the ones that might cause mortality or system failures, and future weather conditions in BPSs.

1.1. Motivations of the study

Mediterranean area has been seriously affected by climate modification in the last few years. This zone is scenario of warm outside conditions and heatwaves, that impact considerably on energy consumption and increase overheating risk in buildings. In the recent years, many locations of this area have registered maximum historical temperatures. Floridia, Sicily, Italy, registered the highest temperature ever measured in Europe, 48.8 °C, in August 2021 (53). During July 2022, Spain registered the hottest month ever measured since 1961, first year of measurements (54). Catalonia in the same year registered the hottest summer of the last 20 years in 107 stations of XEMA (Xarxa d'Estacions Meteorològiques Automàtiques) and the second one in the remaining stations (55). A study of Montlleó (56) on the city of Barcelona, highlighted how heatwaves and warm periods would modify at the end of the century. Studied scenarios, according to IPPC's RCP models, showed that hot days, the ones with temperatures higher than 35 °C, would occur for 30 more days every year in RCP4.5 scenario and 60 more days in RCP8.5 one. In the same way, tropical nights, with temperature higher than 20 °C, would increase by 30 and 45 episodes respectively for RCP4.5 and RCP8.5, causing possible problems on the population, that can experience health and sleep issues and discomfort.

As previously mentioned, major severity of climatic conditions would increase cooling need and the relative consumptions. Studies of Odyssee-Mure (57) evaluated an increment of 30% in Italy and Spain in the period between 2005 and 2009, while the one of Feyen et al. (58) predicted an increment of 40-70% in the years 2010-2050. A study conducted by Vurro et al. (59) on a neighborhood in Bari, Italy, where future weather scenarios have been created for the years 2020, 2050 and 2080, highlighted a continuous increase of cooling need, rising by 37% in 2050 respect to 2020 and by 38% in 2080 respect to 2050.

For reducing the possible risks of future weather, the city of Barcelona proposed a plan for climate action, energy production and consumption and environmental and social sustainability (60). In particular, the city would be modified, adapting buildings to new climatic conditions, increasing green spaces, guaranteeing biodiversity and restoration of coastline, to improve resilience of cities and metropolitan natural spaces. In this project, almost 20% of buildings with more than 40 years would be retrofitted. It is important that improvements of these dwellings will be conducted in an optic of resilience and climate protection, usually distant from the common methodology used for their design.

In this optic, BESs could significantly help in the design of a resilient built environment. Unfortunately, datasets representing future weather and extreme conditions are difficultly available. Because of this, it is necessary to generate them in an accurate way, following several possible methodologies. The most common start from large-scale climate projections, which are afterwards downscaled using statical or dynamical techniques (61). The study of P.Tootkaboni et al. (62) pointed out how dynamical downscaling provides better spatial and temporal variability of local climate, which is essential for verifying the physical consistency of the dataset and its reliability in case of resilience assessment.

1.2. Objectives of the study

There is an urgent need of testing energy performances and resilience of building in the Mediterranean area. In literature there are few studies about resilience of residential buildings in Catalonia, in case of present and future climatic conditions and heatwaves. At the same time, examples for resilience to power outages are not present. In addition, analysis of energy needs, with environmental and economic impact of its satisfaction, under future climate scenarios are present but not sufficient for constituting complete guidelines for the creation of a resilient built environment.

For these reasons, the objectives of this study are:

- The creation of future weather scenarios for the city of Barcelona, representing new average climate conditions and possible extreme events, such as heatwaves and power outages. They should be created using a dynamical downscaling method and converted in a format suitable for building energy simulations.
- Testing the actual building under these new conditions, understanding modifications respect to historical scenario and identifying criticalities on resilience, comfort and energy needs.
- Testing different cooling technologies in the building, assessing their contribution to resilience and comfort under average conditions, heatwaves and power outages.
- Evaluating modifications on energy needs and consumptions, with the relative environmental impact and costs, related to the implementation of the different cooling techniques.

2. Theoretical framework and Literature review

Before the formulation of a methodology for achieving the proposed objectives, it is important to report definitions, frameworks and the state of the art of the topics of interest. For the weather scenario, the models proposed by IPCC will be presented, visualizing the different methods for obtaining the climate projections. The different definitions of heatwaves and power outages will be also studied, investigating the ones adopted by organizations and groups of research. Latterly, the concept of resilience will be studied, starting from its definition, passing from the possible technologies that can be applied and arriving at the indicators used for its evaluation. Finally, results of previous studies regarding this characteristic of building in case of severe weather conditions and power outages will be shown.

2.1. Weather data

2.1.1. Climate Projections

Climate projections are forecasts of changes in temperature and atmospheric conditions that are related to human choice (63). IPCC proposed Representative Concentration Pathways (RPCs) for describing various paths for GHG and air pollutant emissions and their atmospheric concentrations (2). They are selected and categorized according to their total radiative forcing, which is the increase in solar power radiation per square meter of land brought on by the presence of GHG in the atmosphere (64). Four scenarios are included in RCPs: a strict mitigation one, RCP2.6, two intermediate ones, RCP4.5 and RCP6.0, and one with high GHG emissions. This last scenario maintains the actual incrementative trend of emissions for the whole century, in contrast, the other ones include possible decrements as results of potential mitigation actions. According to the RCP, temperature would increase by a variable value by the end of the 21st century (2). The different scenarios represented by the RCPs are shown in the table below.

Scenario	Description	Prevision of emissions	Average Surface Tempertature Increase
RCP2.6	Aggressive Mitigation	Global greenhouse gas emissions start decreasing after about a decade and to reach near zero levels around 60 years from now	0.3 °C – 1.7 °C
RCP4.5	Early Stabilization	CO_2 emissions fall below current levels by 2070, atmospheric concentrations stabilize by the end of the century at about twice those of the pre-industrial period	1.1 °C – 2.6 °C
RCP6.0	Late Stabilization	CO_2 emissions continue rising until about 2080; concentrations take longer to stabilize and are about 25% higher than for RCP4.5	1.4 °C – 3.1 °C
RCP8.5	Businness-as-usual	By 2100, atmospheric concentrations of CO_2 are three to four times higher than pre-industrial levels	2.6 °C – 4.8 °C

Table 1: RCPs Scenarios – adapted from (2) *and* (65)

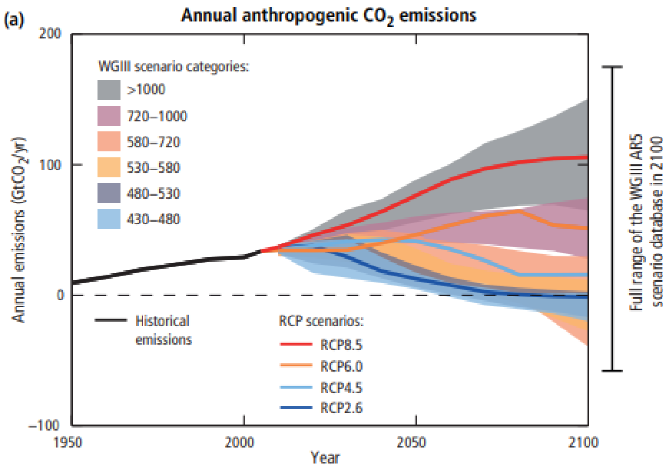


Figure 5: Emissions of carbon dioxide (CO2) of each Representative Concentration Pathways (RCPs) - from (2)

2.1.1.1. Global Circulation Models

Based on mathematical equations that describe processes, interactions and feedbacks of atmosphere, oceans and biosphere, General or global circulation models (GCMs) are tools that are used to understand current and future climate scenarios at global, hemispheric and continental scale (with spatial resolution usually between 150 and 600 km^2) (66) (67). One model is the union of many grid cells that represent horizontal and vertical areas on the Earth's surface. In each cell, a computational analysis of water vapor and cloud interactions, aerosol effects on radiation and precipitation, snow and sea ice cover, heat storage and fluxes in soils, surfaces and oceans and large-scale transport of heat and water by atmosphere and oceans is performed (68). Since each model grid cell produces a single value for a given variable, GCMs provide quantitative estimations over global and continental scale and over long periods.

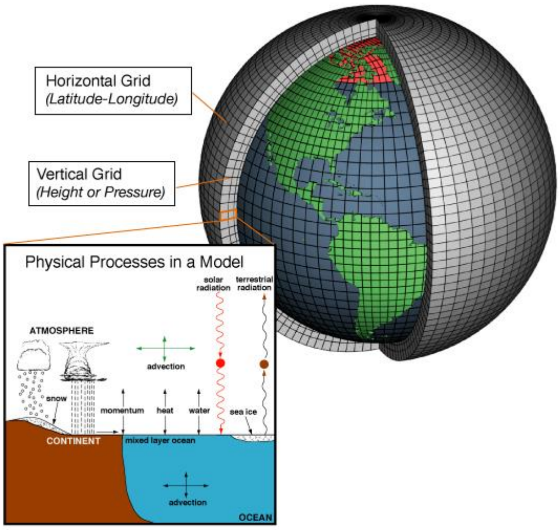


Figure 6: Conceptual structure of a GCM - from (66)

2.1.1.2. Downscaling

Even though GCMs give good climate projections, for most of the business, stakeholders and society needs, finer models, with the size of a region or a location (less than 100 km^2), are required (69). In the studies of Rummukainen (70) and Lindberg et al. (71), landscapes characteristics such as mountains, water bodies, infrastructures and land covers were defined as crucial parameters for decision making on hydrology, productions and species distributions. For these reasons, various methods have been developed to solve this gap. As explained by Seaby et al. (72), starting from large-scale models, adding local features and information, it was possible to derive realistic outputs for finer spaces and time. The two approaches used for increasing spatial and temporal resolution of GCMs are the following:

- Statistical downscaling, that establishes empirical relationships between historical or current local climate variables and large-scale climate data, used for modifying current weather data (73). One of the most used "morphing methods" was developed by Belcher, Hacker and Powell in 2005 (74). Their algorithms consist of applying shifts, stretches and a combination of both to adjust present-day data to reflect future projections. In this case, GCMs are used as reference model for the creation of the modified data.

- Dynamical downscaling, that relies on the use of regional climate models (RCM), similar to GCMs but with a higher resolution. An RCM is a proper numerical climate prediction model, where large-scale atmospheric information, provided by a GCM, are incorporated in a complex topography, with surface heterogeneities, ocean and detailed physical processes (72). Despite RCM spatial resolution can be between 20 and 50 km, its outputs are affected by systematic errors and uncertainties, caused by GCM large-scale accuracy and biases (75). For this reason, this type of data requires a bias correction, based on historical observations of the specific site (76). In addition, RCMs provide a large variety of outputs, that can be very advantageous for comparing models and creating representations of extreme events, such as heatwaves (77) (78) (62).

2.1.2. Heatwaves

One of the most frequent extreme events caused by climate change are heatwaves. They are generally defined as "*a period of unusually hot weather*", by the Oxford Advanced Learner's Dictionary (79). Although, for guaranteeing a better understanding of the phenomenon, this definition is not adequate and a major level of detail is needed. Among the academic and institutional words, there is not a unique definition of this type of event. As highlighted by Koppe et al. (80) and Robinson (81), they are usually related to geographical location, which implies different environmental parameters and sociological factors. De Boeck et al. (82) explained as climatic, temporal and statistical magnitudes of interest are commonly compared to fixed or relative thresholds, that allow the identification of the event. They found fixed thresholds strongly dependent on the location where they are implemented, since they are not able to consider possible variations of the different climatic zones. The authors, on the other hand, assessed that the use of relative magnitudes, like percentiles, allows to apply the selected methodology to different geographical areas.

Some methodologies for detecting and characterizing heatwaves are reported in this section. One indicator based on absolute thresholds was proposed by Frich et al. (83). In their study the duration index of the heatwave is calculated as the sum of the consecutive days with a maximum temperature that exceeds the daily maximum one of the years between 1961 and 1990, being 5 days the minimum duration of the period. This index has been criticized for the low consideration of daily temperature variation differences between the different locations of the world (82) (84). Argentinian National Meteorological Service (85) proposed a definition of heatwave considering threshold temperatures of the site, based on conditions of 1961-2010 period. A heatwave is defined as "the period of at least 3 consecutive days when both maximum and minimum temperatures are simultaneously greater than the threshold temperature (90^{th} percentiles) for the site" (86). Another method based on threshold values was elaborated by Ouzeau et al. (87), basing the detection and characterization of an extremely warm period on its duration, maximum temperature and severity. Three thresholds are defined, corresponding to 99.5, 97.5 and 95.0 percentiles, used for determining duration, intensity and severity of heatwaves. This method, at first used for France, was validated using a CORDEX climate dataset (88).

Other methods take into account heat stress and mortality caused by heatwaves. In Australia, Fawcett and Nairn (89) proposed a new index, called excess heat factor (EHF), able to consider progressive adaptability of the human body to warm temperatures. In their model, a period of acclimatization of 30 days is considered, defining two indicators, called significance and acclimatization indexes, for determining long and short-term temperature anomalies respectively. In case of a period longer than 3 days, a threshold evaluates if the heatwave could be considered severe.

2.1.3. Power Outages

Power outages are interruptions in the supply of electricity (90). They are caused by natural events, like storms, lightning and earthquakes, equipment failures and human activities (91) (92). For this reason, they have a major probability to occur during severe weather conditions, periods of high electricity demand and maintenance (93). The phenomena that cause the events and the context where they happen are key factors for their duration, that can be of few hours or many days.

There are many reports and studies that highlight the impact of climate change on the frequency and duration of these events. The study of Shield et al. (94) points out that 50% of outages in the U.S. are related to weather issues, especially thunderstorms, with an average restoration time of 5 days. Eto et al. (95) analyzed the failures occurring in 155 U.S. electric utilities in a period of 10 years. They discovered that reliability of the grid decreased through the years, with an annual trend of 2%. However, this result could not be strictly related to a higher frequency of extreme events, but it was probably connected to more accurate measurements of reliability. A latter work of the same authors (96), on the other hand, pointed out that there is no significant relationship between lower reliability and improved accuracy of measurements. In this optic, grid reliability has been affected by worse climatic conditions, suggesting a major preparation and recovery from large events. In a final work proposed by them (97), the costs related to future weather conditions, under RCP4.5 and RCP8.5 scenarios for the whole century, are evaluated. It was found that more severe conditions correspond to higher costs associated with power outages, especially for the years after 2060. In addition, they evaluated the possible savings obtained by a major resilience of the grid, that are not always cost-effective.

2.2. Resilience

2.2.1. Resilience definitions

Resilience is defined by Oxford Dictionary as “*the ability of people or things to recover quickly after something unpleasant, such as shock, injury, etc.*” (98). It is a complex concept, having different connotations in the various disciplines of its application.

From the psychological point of view, American Psychological Association (99) and Southwick et al. (100) related it to the mental and emotional adaptation of a person to the difficult or challenging experiences, taking advantage from his/her personal characteristics or external support. Bonanno et al. (101) agreed on the distinction of resilience from mental recovery, being the resilient individual able to generate positive emotions and to fulfill responsibilities. In this optic, Graber et al. (102) defined resilience as the "*ability to adsorb*" the shock and the "*positive adaptability*" in response to it.

Ecological resilience proposed by Walker et al. refers to "*the capacity of a system to absorb disturbance and reorganize while undergoing change so as to still retain essentially the same function, structure, identity, and feedback.*" (103). As explained by Simmie et al. (44) and Holling (104), this concept includes the possibility of the system to find a new point of equilibrium, found with arrangements and adaptations to new conditions. In this way, it is described as the ability to "*bounce back*" the shocks.

In the field of engineering and economics, Holling defined resilience as "*how fast a system that has been displaced from equilibrium by a disturbance or shock returns to that equilibrium and continues performing.*" (44). It differs from the ecological concept since its objective is returning to the original equilibrium state, as fast as the system is resilient. For this reason, Simmie and Martind (104), as well as Attia et al. (105), indicated it as the ability to "*evolve*" over time and "*bounce forward*" from disruption.

2.2.2. Resilient cooling for buildings definition

In the last years the interest in resilience of the built environment increased considerably. It can be assessed in response to different natural disrupting events, political and economic crises or attacks against communities (106) (101). In the engineering domain, the first type constitutes an important point of research. A significative contribution to its definition was provided by the works of IEA-EBC Annex 80 (43) and Attia et al. (105). After a preliminary analysis, the authors decided to define boundary conditions of the studies, setting spatial and time scales. Resilience is investigated at building scale, for single building element, building service or entire facility. It is assessed in case of heatwaves and power outages, that constitute a significant hazard for occupants, increasing overheating risk inside the dwellings. Analysis should be conducted for the whole century, using climate projections, to understand both actual and future response of buildings and technologies to new weather conditions.

According to the scope of the IEA-EBC Annex 80, resilient cooling denotes *"low energy and low carbon cooling solutions that strengthen the ability of individuals and our community as a whole to withstand, and also prevent, thermal and other impacts of changes in global and local climates;*

particularly with respect to increasing ambient temperatures and the increasing frequency and severity of heat waves." (43).

Starting from this affirmation and integrating it with other ones found in literature, Attia et al. (105) developed a more complete definition of resilient cooling. They supposed it as a complex process that involves four main criteria, consecutive to each other, shown in Figure 7. The first is vulnerability, that defines exposure risk of building to disrupting events. The authors recommended it as a preliminary assessment of the design process. The second aspect is resistance, that identifies the first reaction to the shocks and the tendency of maintaining the conditions present before. It is function of building design and characteristics of the cooling technologies implemented. The third stage is robustness, that corresponds to the possibility of the system to adapt in response to a first disruption, changing its configuration. Performance is adapted to reach minimum requirements and conditions inside the building. It is guaranteed by flexibility and adaptability of occupants and technologies. The last step is recoverability, consisting of the restoration of the original equilibrium of the system, after failure occurrence. Recovery time, performance and learnability are essential aspects of this phase.

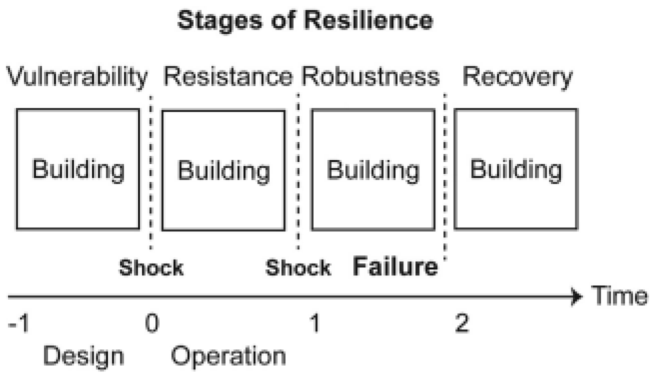


Figure 7: Stages of Resilience - from (105)

As result, the definition of resilient cooling proposed by Attia et al., elaborated with several members of IEA-EBC Annex 80, is the following:

"*The cooling of a building is resilient when the capacity of the cooling system integrated in the building allows it to withstand or recover from disturbances due to disruptions, including heat waves and power outages, and to adopt the appropriate strategies after failure (robustness) to mitigate degradation of building performance (deterioration of indoor environmental quality) and /or increased need for space cooling energy (recoverability)*" (105).

2.2.3. Resilient cooling strategies

Starting from the different phases of resilience, Zhang et al. (107) summarized four many characteristics of resilient cooling techniques:

- Absorptive capacity, that evaluates the degree of absorbing the impacts and minimizing consequence of disrupting events.
- Adaptive capacity, that assesses the ability to adjust parameters or configurations in presence of abnormal situations.
- Restorative capacity, that determines the ability of restoring normal or improved conditions after the disruption.
- Recovery speed, that quantifies the speed of the recovery process.

Considering the wide range of possible cooling solutions that corresponds to these definitions and characteristics, IEA-EBC Annex 80 (43) proposed a list of technologies, categorizing them by their action on the indoor environment. They are presented in the table below:

Category	Cooling strategies
A- Reducing external heat gains to indoor environments	Advanced solar shading, Advanced cool materials, Advanced glazing technologies, Ventilated façades, Green roofs, green façades
B- Removing heat from indoor environments	Ventilative cooling, Thermal mass utilization (hydronic activation, PCM and off-peak storage), Evaporative cooling, Sky radiative cooling, High performance compression refrigeration machines (single split, multiple splits, VRV units and chillers), High performance absorption chillers (desiccant cooling), Natural heat sinks, Solar cooling, Heat recovery systems
C- Increasing personal comfort apart from space cooling	Comfort ventilation and elevated air movement, Micro-cooling and personal comfort control
D- Removing humidity from indoor environments	High performance dehumidification (desiccant humidification)

Table 2: Resilient cooling strategies – rearranged from (43) and (107)

Most technologies of category A and C are commonly recognized as passive cooling strategies, while the ones of category B and D as active strategies (108).

A brief description of measures applied in this work, presented in chapter 3.3, is provided in this section.

Green roof is a specific roof structure designed for growing vegetation on it (109). Plants are usually planted into specific containers, presenting waterproofing membranes, drainage layers, landscapes and mediums for the soil. In case of vegetation like grass or small plants, which do not require high maintenance and irrigation, soil depth is usually between 5 and 15 cm. This type of roof is recommended for retrofit projects and it is implementable for a wide range of roof slopes. It takes advantage of heat flux and evaporation of soil and vegetation layers, that balance temperature differences with air and radiative forcing from the sun (110). Energy performance of the roof is determined by type and condition of plants, soil composition, building type and size and weather conditions. One important parameter is the leaf area index (LAI), a non-dimensional magnitude defined as "*half the total area of green elements of the canopy per unit horizontal ground area*" (111). It is function of vegetation specie, climatic conditions and season, that present different water retention and heat transfer characteristics (112) (113). Some studies correlated reduction of indoor temperature with the increment of LAI, obtaining lower temperatures and energy needs during summer (114) (115) (116). A significant contribution of green roofs in the built environment is to the mitigation of Urban Heat Island effect in dense metropolitan zones, obtained through plant transpiration (117).

Figure 8: Example of green roof installed in a built environment – from (118)

Advanced solar shadings are dynamic shading systems. One of the most typical examples are blinds, installed exterior or interior to the glazing, or into cavities between two glazes. Their porpoise is reducing solar heat gains reflecting and absorbing solar energy (119) (120). Venetian blinds are composed of a set of narrow, horizontal pieces, with a defined design and distance (121). Slats can be made with different materials, such as wood, plastic or metal, that determine their optical properties, and present adjustable inclination. Their use can be managed by occupants, ensuring thermal comfort during both cooling and heating seasons. A critical aspect of this measure is the conflict between energy and visual performances, since the improvement of one penalizes the other, requiring a compromise between them. Exterior installation of this device results much more effective in reducing solar gains rather than interior setup (119).

Figure 9: Blinds and Advanced glazing – from (122) and (123)

Advanced glazing is a glazing technology with high performance in reducing energy needs of buildings. It is effective during both cooling and heating seasons, controlling thermal and solar radiation transmission (124). It is characterized by three main optical parameters, reflectance, absorptance and transmittance (125). This last parameter, combined with the secondary emission of absorbed radiation, is used for calculating the solar heat gain coefficient, that quantifies the total fraction of the incident solar radiation that enters through the window (126). Modern techniques of construction allow to minimize solar heat gains and thermal transmittance, without penalizing visual comfort. The most common use special coatings for reducing emissivity of thermal radiation (Low-e), that increase reflection and absorption, or present multiple glazing with vacuum or gasses between them, that significantly improve thermal insulation (127) (128).

Natural ventilative cooling, according to ASHRAE, is a cooling technology that spreads passive technique of ventilation "*driven by pressure differences across the building envelope caused by wind and air density differences*" (129). It depends on both driving mechanisms and characteristics of openings in the building envelope. Stack, or buoyancy, effects are determined by differences of air density, function of local barometric pressure, temperature and relative humidity (129). In case of temperature inside the building higher than the one outside, the indoor environment is depressurized compared to outdoor. This difference of pressure causes a flow of fresh air into the building. Other pressure differences are created by wind flow around the facility, that in general are positive respect to indoor spaces. They are determined by wind speed and direction, air density, surface orientation and surrounding conditions. Considering the characteristic of these two contributions, location and exposition of the building and its geometric characteristic are important boundary conditions for the effectiveness of this type of ventilation (130). It can be used during both daytime and nighttime (131). The first guarantees occupants comfort directly removing heat gains, reducing indoor temperature and improving evaporative cooling effect of occupants' skin. The second decreases temperature and permits an enhanced dissipation of stored heat in the envelope of the building, related to its thermal mass.

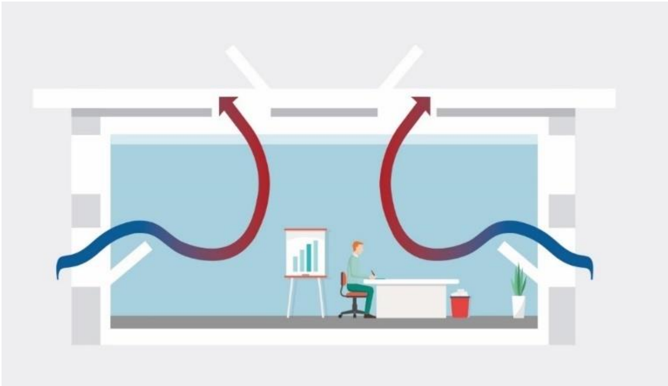


Figure 10: Schematic working principle of ventilative cooling – from (132)

Vapor compression refrigeration is the common expression for indicating Vapor Compression Air Conditioning units (ACs), active technology able to produce a cooling effect (107). The system is composed of four main parts, where a refrigerant fluid is compressed, condensed, expanded and evaporated, following a thermodynamic cycle (129). Design and size of the machine are key aspects for determining its cooling capacity and consumptions, also related to characteristics of the cycle and ambient conditions. The parameter that quantifies its cooling power compared to mechanical energy required is the Coefficient of Performance (COP), that is as high as the device is efficient and performant (37). Units are classified by heat source and sink, chillers, function, modes of use, configuration and refrigerant type. These characteristics determine the range of cooling capacity and size of the unit, defining its possible implementations.

2.2.4. Resilient cooling indicators

Essential elements for the assessment of building's performance are globally recognized frameworks and indicators. Actually, the ones used for resilience do not have official recognition, but they are discussed and shared between groups of researchers. For this reason, two of the objectives of IEA-EBC Annex 80 are the identification of resilience indicators, useful for the assessment of this property, and the provision of frameworks and guidelines for considering it during the design phase of buildings (43).

Indicators used for evaluating resilience can be related to building performances or occupants' feelings and behavior. Some of them are used for several applications that differ from resilience, while others are specially created for this scope (133).

Comfort indicators are widely used for resilience assessment in literature. They are usually functions of climatic parameters, like air temperature and relative humidity, that influence human thermoregulation, and psychological ones, referring to expectations and adaptation of the individuals

(134) (135). First possible indicators can be Operative temperature and Predicted Mean Vote (PMV), widely used for building design and cited in international regulation (134) (136) (137). Basing on threshold values, it is possible to evaluate magnitude and duration of thermal discomfort, usually in terms of annual hours of exceedance (HE). Other examples include Heat Index (HI), used in the United States, and Humidex (H), widely used in Canada (138) (139). The first is function of dry-bulb air temperature and relative humidity, while the second considers air temperature and dew-point temperature (140). Their values are associated to different levels, that correspond to conditions of comfort, discomfort, possible illnesses, fatigue or strokes directly related to sensations of heat. Another indicator related to thermal comfort is Standard Effective Temperature (SET), proposed by Gagge et al. (141), based on a two-node model for human heat-balance equation, able to account environmental and the physiological regulation.

The introduction of resilience concept started the scientific research of new indicators for its assessment. Some of them use curves for its evaluation. It is the case of resilience triangle and trapezoid. The first was formulated by Bruneau et al. (142), considering the percentual quality of an infrastructure respect to time. A disrupting event causes an instantaneous decrease of quality, that is gradually recovered during time. Resilience is function of the starting decrement and the recovery speed. A similar approach was proposed by Panteli et al. (143), that substituted the triangular shape with a trapezoidal one. In this formulation, gradual declination of resilience level and maintenance of the degraded state are considered, providing a more accurate understanding of the phenomenon.

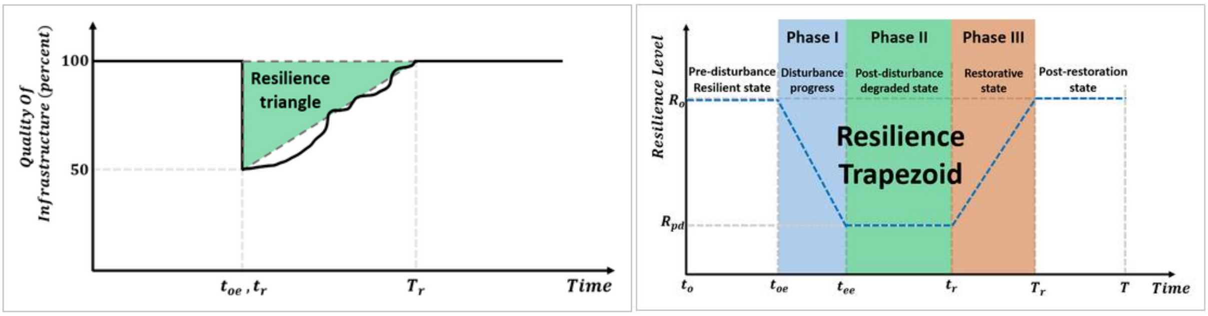


Figure 11: Triangle and Trapezoid of resilience – from (142) *and* (143)

Basing on the same approach, Homaei and Hamdy (144) formulated the weighted net thermal performance (WUMTP) for evaluating building resilience. It considers the two phases during and after the disrupting event, enriched by hazard levels and exposure times. Starting from these three elements, three penalty factor types are applied, useful for the evaluation of the performance indicator. Comparing it with one of reference, the resilience class is assessed. Ji et al. (145) highlighted WUMPT's limitation of not considering relative humidity and psychologic parameters. They proposed a new indicator, the weighted standard effective temperature (WSETH), having the same formulation of WUMPT but using SET instead of operative temperature. In addition, it can evaluate resilience class at the whole building level, averaging the different WSETH of each space on their total surface. A different typology of resilience indicator was formulated by Hamdy et al. (146), that quantifies overheating inside a dwelling compared to the warmness of outside, understanding if the building resists severe climatic conditions. This indicator, called overheating escalation factor (α), that is based on the almost linear correlation between indoor overheating and outside temperature, can assess resilience of the whole building, taking into account possible differences of setpoint temperatures and hours of occupancy. The use of these indexes was suggested by Attia et al. in their framework for assessing resilience of the different cooling strategies (133). A new version of α, named Climate Change Overheating Resistivity Factor (CCORF), is proposed by the same authors (147), with the objective of evaluating a unique parameter for the different building configurations and technologies implemented, that averages the results obtained in the overheating assessment during different climate scenarios.

Energy efficiency and sustainability of buildings are key aspects in the definition of resilient cooling. In addition, they are necessary elements for guaranteeing optimal indoor conditions. For this reason, they can be used for the evaluation of resilience. Framework of Attia et al. (133) proposed some energy metrics as outputs of resilience evaluation, such as annual heating and cooling need for conditioned space and peak load.

2.2.5. Previous studies on resilient cooling for buildings

In the last years many studies regarding resilient cooling for buildings have been developed. They have been made by different groups of research and institutes, that spread different metrics and approaches for resilience assessment. Several of these works investigate climate modification and resilience of buildings in the Mediterranean area.

A complete overview is provided by the dissertation of Pourabdollahtootkaboni (148) on climate resilient and energy efficient buildings, where impact of climate change on different types of dwellings in Italy is evaluated. Results showed an evident increase in cooling electricity consumption related to future climate modifications, as on the risk of indoor overheating, with a particular impact in long term scenarios and specific climate zones. Refurbishment allowed to reduce buildings' sensitivity to new conditions, but it could lead to a major presence of uncomfortable conditions during summer period. For this reason, several resilient cooling techniques have been applied in residential buildings, during different time periods. Mechanical ventilative cooling and ultra-selective double-glazed windows resulted the best solution for increasing energy efficiency and reducing hours of exceedance in free-floating conditions, especially for post-retrofitted buildings. Although, the benefits of the first decreased over time because of higher outdoor temperatures. Building's envelope insulation level was assessed as the main factor for the determination of thermal cooling need and electricity consumption, while interactions between envelope and cooling technologies played a significant role for comfort in free-floating regime, confirming the importance of trade-off between energy efficiency and climate resilience in future weather scenarios.

Hamdy et al. (146) conducted a study on thousands of Dutch dwellings built between 1964 and 2012, evaluating overheating risk and resilience during summer of historical and future scenarios. It was found that 97% of the dwellings was able to resist global warming. Buildings with high solar heat gains and low heat transmission resulted more exposed to overheating risk, independently from the time period. Differences have been detected between floors of the buildings, with the upper ones more likely to achieve warm indoor conditions, especially in old buildings with low insulation and solar protection. Low or minimum ventilation rates also significantly contributed to overheating occurrence, with vulnerability increasing through the years, suggesting the update of prescriptive design values. According to this, the authors recognized ventilative cooling and solar protection as best measures to combat warm conditions, highlighting the decremented potential of the first during future scenarios, that would increase the use of other active measures.

Results found by Flores-Larsen and Filippin (149) showed the inadequacy of old and low-income housing, not equipped with vapor compression refrigeration or not used for economic reasons, during heatwaves in Argentina. Simulations evaluated that combination of night ventilation, shading of the envelope, such as green walls and ventilated facades, and improved roof could reduce indoor temperature of 3 °C and cooling load of 37% compared to the base configuration. Other auxiliary cooling systems, like evaporative coolers, have been suggested for achieving better interior conditions and reducing electricity consumption, improving heat resilience of the building.

The work made by Ji et al. (145) highlighted the importance of assessing resilience during heatwaves at whole-building level with the use of specific indicators. Retrofit strategies resulted more effective on upper floors rather than the lower ones. For this reason, adequate measures should be applied to less-resilient zones, guaranteeing the improvement of global resilience of the building. Among the studied cooling technologies, natural ventilative cooling and exterior shading were the most recommended for the most overheated spaces. However, efficiency of each technique was affected by the others already implemented, resulting almost ineffective for buildings that already had a high resilience class.

Borghero et al. (150) conducted a study on an apartment located in Badalona, where resilience of different active technologies was evaluated during average summer and heatwave periods of present and future years. The authors found that during common present weather conditions, natural and mechanical ventilation guaranteed optimal level of comfort and resilience, consuming an amount of energy 6-10 times lower than the one used by vapor compression refrigeration. However, their effectiveness was compromised during heatwaves and future climate, when AC was required for maintaining safe conditions. This last aspect is extremely relevant, considering that 45% of actual

Catalan buildings do not have AC installed and its continuous use could lead to power outage phenomena. A key role for building's resilience was played by the occupant, who could adjust natural ventilative cooling and shading use whenever it was necessary, achieving results much better than simple passive measures (151). Ventilation has been defined as an essential parameter for guaranteeing resilience of the building, also in case of warm or extremely warm outside temperatures, despite its low effectiveness on increasing indoor thermal comfort.

Resilience in case of power outages during historical heatwave periods was investigated by Sun et al. (152), who simulated conditions inside a nursing home in the United States. In particular, trade-off between energy efficiency and thermal resilience of the different techniques was evaluated. Natural ventilative cooling was the most effective measure for reducing thermal discomfort, while other passive measures, such as cool roofs, new windows and higher insulation, contributed to the reduction of dangerous conditions but did not guarantee safety inside the building. Cool energy storage or PV panels for providing half capacity of cooling systems have been defined as necessary measures for safety of occupants. A latter work on the same facility during heat waves and cold snaps with power outages was conducted by Sheng et al. (153). Extreme weather periods for the city of Houston have been detected using the thresholds proposed by Ouzeau et al. (87). Contribution on resilience of cooling techniques in hot weather days was the same as the previous study (152). Interesting results come out from the analysis during cold snaps, highlighting an opposite effect of passive measures, especially from the ones that reduce solar gains and infiltrations, that penalized thermal resilience. For this reason, the authors suggested considering both hot and cold periods in the resilience assessment during power outages. Techniques that improved performances in both situations were related to wall and roof insulations, that, integrated with other flexible measures, could guarantee a significant reduction on energy needs and peak and backup power of the building.

Two studies on nearly Zero-Energy buildings in Belgium assessed their resilience in case power outages occurrence during present and future extreme weather events. The first was elaborated by Rahif et al. (154), who optimized the design considering both energy use and thermal comfort. Combination of high ventilation and low infiltration rates, high insulation and thermal mass, green roof and roller blinds obtained an increment of 32% on energy efficiency and 46% on thermal comfort. Other parameters like building orientation, roof and wall solar reflectance and solar heat gain coefficient of windows resulted advantageous during one season, but they penalized energy needs and comfort in the other one. The authors evaluated that, in case of power outage during heatwaves, none of the possible configurations could avoid overheating phenomena, recommending a major preparation of building and occupants in the future. The second study, proposed by Sengupta et al. (155), assessed resilience during both TMY and HW periods. Night ventilation, indirect evaporative coolers and shading guaranteed thermal resilience to overheating during TMY, but resulted insufficient in case of HWs. Thermal mass achieved positive results on resilience during hot periods, but it led to bad effects on heat retention after power outages, maintaining uncomfortable conditions for a long time.

3. Methodology

The objective of this work is assessing the impact of different cooling techniques on the resilience, energy needs and consumptions of a residential building in Barcelona, during present and future scenarios of typical and extreme weather. The methodology used in this work is inspired by the framework for evaluating resilience of cooling technologies proposed by Attia et al. (133), members of IEA-EBC Annex 80 taskforce (43).

The central core of the workflow is constituted by the simulations of the dynamical thermal conditions inside the building, performed with a model created for this scope. It is developed using specific applications, able to draw geometry, set envelope and equipment characteristics and define function, schedules and loads of the building. Passive and active cooling technologies can be modelized and implemented in the model, as part of its envelope characteristics or dynamical components. An important role in the simulations is played by input weather data, that represent annual average conditions or extreme events, such as heatwaves and power outages. They have been created from regional climate projections of future years of the century, corrected with historical observations and elaborated in a format compatible with the simulation program. Outputs of simulations are post-processed, evaluating the different parameters and measurements, useful for assessing starting performances of the building and determining the effect of the technologies implemented. Results are also essential for choosing and sizing the measures to apply.

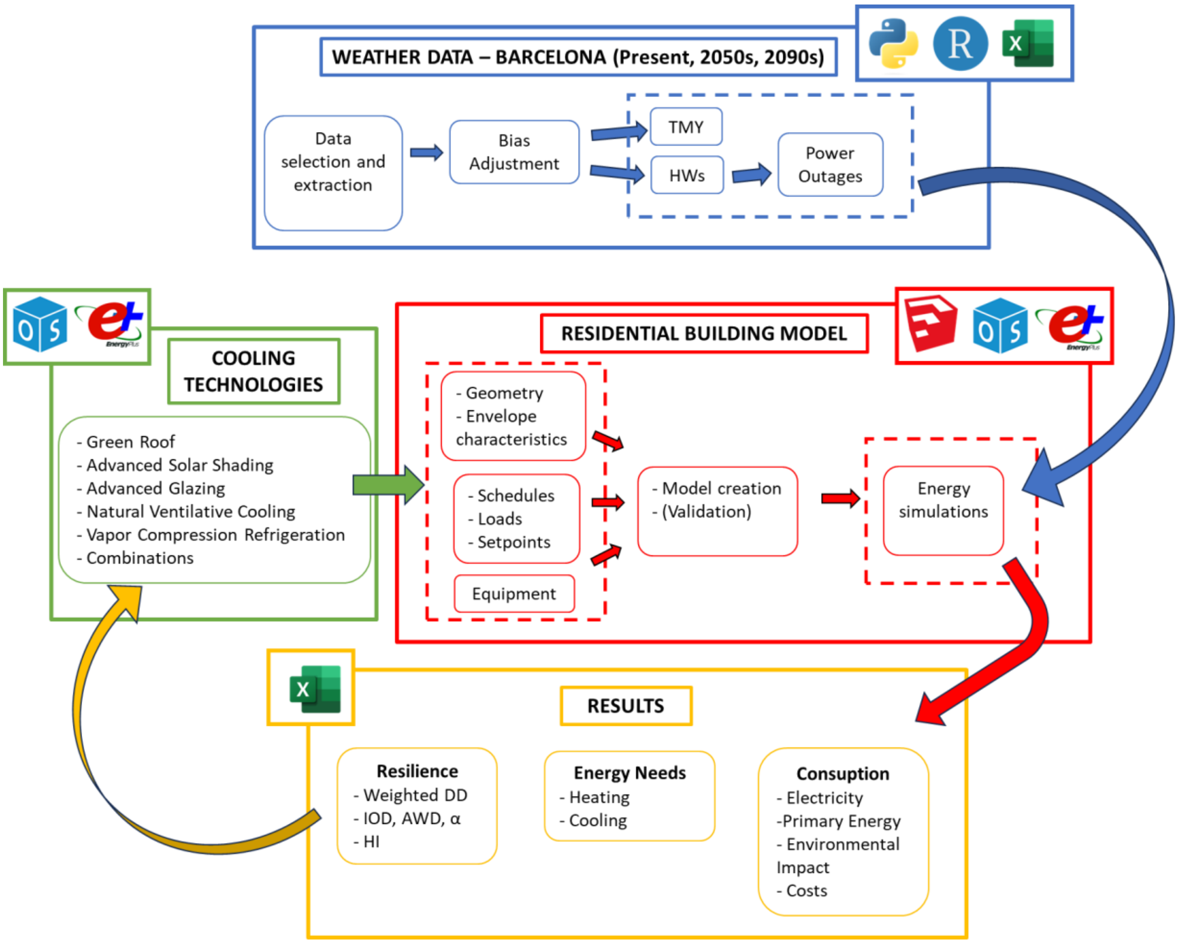


Figure 12: Workflow

3.1. Weather data

One important part of this work is the use of sets of meteorological data that simulate probable weather conditions of next decades. They allow to predict how the technological solution implemented in the building would perform in future scenarios, where parameters can be significantly different from the ones that are present today.

The methodology that is used for the creation of these new weather data was developed by the Weather data Task force of IEA EBC Annex 80 Resilient Cooling of Buildings (156) (157). Its aim is the improvement of energy building simulations and, consequently, the creation of technical profiles of existing and new low carbon, low energy and resilient cooling solutions. Following their instructions, two weather data types, Typical meteorological year (TMY) and Heat wave (HW), for three different scenarios, Present, Medium Term Future and Long Term Future, are developed. The two typologies of data allow to investigate resilience and energy performances of the different technologies under ordinary and extreme conditions, essential for their selection and sizing. Whereas, different time periods can help in view of future improvements.

The three periods investigated are presented in Table 3:

Scenario	Present	Mid-Term Future (50s)	Long-Term Future (90s)
Years	2006 -2025	2041-2060	2081-2100

Table 3: Time periods considered in weather data creation

3.1.1. Weather data selection

The necessary data for the creation of TMY and HW weather files have been downloaded from Lawrence Livermore National Laboratory website of the Department of Energy of United States of America (DOE) (158) (159). The simulations have been analyzed and managed by the Earth System Grid Federation (ESGF) (160). RCMs were generated within the Coordinated Regional Downscaling Experiment (CORDEX) project, a program sponsored by World Climate Research Program (WCRP), with the objective of generating regional-scale climate projections for impact assessment and adaptation studies according to IPCC AR5 (161) (162). The Driving Model and the downscaling method selected is the MPI-M-MPI-ESM-LR/REMO 2015, created by the Max Planck Institute for Meteorology (MPI-M), well supported in literature (163) (164). Data of Europe domain, EU-11, are available with one-hour frequency. For each scenario, seven meteorological parameters have been downloaded: near surface air temperature, near surface wind speed, total cloud fraction, surface downwelling shortwave radiation, surface air pressure, near surface relative humidity, near surface specific humidity. Some of them can be used directly, others need to be modified or split in other magnitudes, as weather files format for simulations requires.

CORDEX data are in NetCDF (Network Common Data Form) format, popular for storing multidimensional data and metadata. One single file can be imagined as a multidimensional array, with different variables that can have multiple dimensions (165) (166). Each one contains dimensions, variables and attributes, that together give a meaning and an orientation to the dataset. One example could be the air temperature of a zone, that varies with latitude, longitude and altitude (167). This type of data can be extracted with the use of Python libraries or specific extractors.

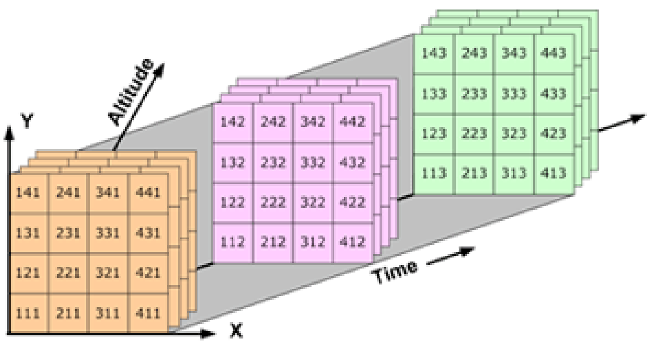


Figure 13: Simple representation of a NetCDF file for air temperature (168)

In addition to predicted weather data, historical data for the city of Barcelona are necessary. Measures are recorded and elaborated by meteorological stations, usually located in the airport or strategic places. For the city of Barcelona, there are several stations, most of them owned by the Servei Meteorològic de Catalunya (METEOCAT), others by Spanish private companies, like Meteoclimatic (169) (170). Considering the typology of the building of this study and the availability of historical data, the best station from which downloading historical data is the METEOCAT automatic station of el Raval, located on the roof of the Universitat de Barcelona (171) (172). El Raval is one of the oldest Barcelona neighborhoods, located in the district of Ciutat Vella. The district is characterized by extremely dense and compact irregular blocks and narrow streets (173). The average height of the building is 17 m and most of the streets are close to the vehicles. In this urban structure, urban heat island effect is often present (174) (175). Meteorological station can partially assess its effects on weather parameters, useful for the creation of future data. Four meteorological parameters are available for the station of el Raval, with 1-hour frequency: near surface air temperature, surface downwelling shortwave radiation, surface air pressure and near surface relative humidity.

Figure 14: Street of El Raval, Barcelona – from (176)

3.1.2. Data extraction and Bias adjustment

Once the CORDEX data have been downloaded, it is necessary to extract only the data relative to the location of the study. Selected values of altitude, latitude and longitude are the same of the weather station of el Raval, respectively equal to 33 m, 41.38° N and 2.17° E. For all the files of each weather variable, the distance between these coordinates and each grid point of the NetCDF file is calculated. In this way, the grid point closer to the selected location is chosen, accessing the variable through the time dimension. Data are extracted and organized in databases of 20 years.

Since climate projection models have big resolutions, present computational and time limits and inability to have feedback, they are always exposed to systemic errors and biases. For this reason, a bias adjustment of data is necessary. Since weather variables usually interact together, a

Multivariate Bias Correction (MBCs), that adjusts multiple variables simultaneously, considering their statistical dependencies, should be performed (177). At first, random orthogonal rotations are applied to observed and modeled weather data, to remove all the correlations between variables. Then, a univariate Quantile Delta Mapping (QDM) is applied to each variable (178). It is an algorithm that detects systematic distributional biases between quantile mapping of observations and modeled data. These quantile deltas are applied to the detrended quantiles of future single variables, correcting them without affecting the differences related to the climate model projection (179). Then applying an iterative reshuffling procedure and latterly inverse random matrices, dependency structure between single corrected variables is restored, obtaining a bias adjusted future dataset.

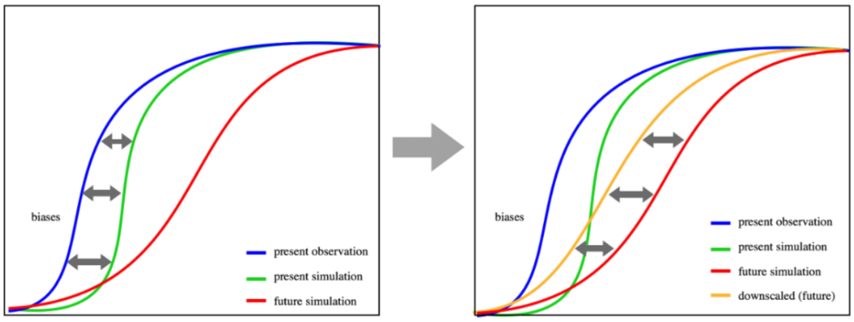


Figure 15: Statistical Downscaling using Quantile Mapping – from (180)

3.1.3. TMY and HWs dataset assembly

Once the 20-years bias adjusted weather file are prepared, it is possible to assemble the Typical Meteorological Year (TMY) for each scenario and to detect the heatwaves occurring. TMY is defined by the Team E3P of the European commission as "*a set of meteorological data with data values for every hour in a year for a given geographical location. The data are selected from hourly data in a longer time period (normally 10 years or more). For each month in the year the data have been selected from the year that was considered most "typical" for that month*" (181). There are several methods for evaluating it, based on climate variables. In its first formulation, proposed by Hall et al. (182) in 1978, the selected parameters were dry bulb temperature, dew point temperature, wind velocity, and solar radiations on a horizontal surface. The methodology used in this work for TMY and heatwave creation is the one proposed by Machard et al. (88).

3.1.3.1. TMY

According to the work of Machard et al., for the creation of the typical years, dry-bulb temperature, relative humidity and global horizontal radiation are chosen as parameters of first order (p), whereas wind speed as the one of second order (88). As explained from the authors, for each month (mo), daily values of each first order magnitude are calculated and put in ascending order series over 20-

years period, L, and in ascending order for each year (y) of the period, J. With them, the distribution functions Φ and Ψ are calculated (88):

$$\Phi\ (p, mo, i) = \frac{L(i)}{N+1} \quad (1)$$

$$\Psi\ (p, y, mo, i) = \frac{J(i)}{n+1} \quad (2)$$

With n the number of days of the selected month and N the number of days of the selected month along the 20-years period. Using these distributions, the Finkelstein-Shafer statistic (FS) is evaluated (183):

$$FS(p, y, mo) = \sum_{i}^{n} |\Psi\ (p, y, mo, i) - \Phi\ (p, mo, i)| \quad (3)$$

The FS of each parameter is classified in ascending order for each month of each year, attributing a rank. The ranks of all parameters are summed and for each month the three years with the lowest equivalent sums are selected. The final choice of the best month is made considering the secondary parameter, the wind speed. The month with the lowest difference between the monthly average of each year and the monthly average of the 20 years is selected. Repeating this procedure for each month, it is possible to assemble the most typical year of each scenario.

3.1.3.2. HWs

There are several methods for defining and detecting heatwaves, based on effects on health or meteorological parameters values. The one that is used in this work is proposed by Ouzeau et al. (87), created for France but suitable for any location and time series. It is based on the evaluation of three percentile thresholds along the whole 20-year period, Spic, Sdeb, Sint, corresponding to 99.5, 97.5 and 95.0 percentiles. The first is used for detecting a heatwave, the second for identifying its duration and intensity and the third for merging two consecutive heatwaves in case of any significant temperature drop. According to this methodology, only heatwaves with a minimum duration of 5 days are considered and if the distance between two events is lower than 3 days, they are considered as a unique event (87).

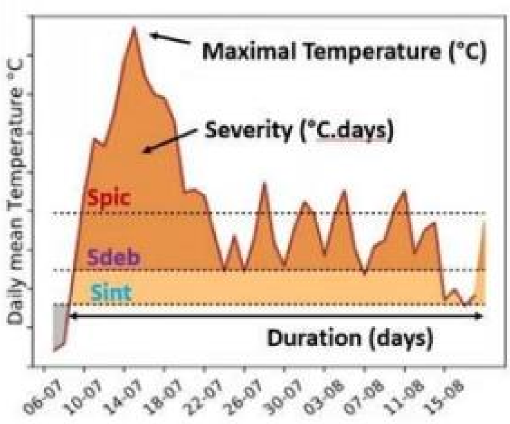


Figure 16: Heatwave thresholds and characteristic elements – from (88)

Heatwaves are characterized by duration, maximum temperature, that identify its intensity, and severity (87). This last is calculated as the sum of the positive difference between the mean temperature of each day of heatwave and the threshold Sdeb, divided by the difference between the Spic and Sdeb thresholds (87). For each time period, three types of heatwaves are detected: longest, most intense and most severe. It could happen that the same heatwave is defined as the one with the highest value in more than one characteristic.

At the end, each TMY and HW dataset is converted in a format useful for energy simulations, the Energy Plus Weather File (epw) format (184). Before the conversion it is necessary to split solar global horizontal radiation in its component of direct normal irradiance and diffuse horizontal irradiance and to add wind direction, taken from other historical weather files for Barcelona, since projections are not available for this magnitude.

3.1.4. Degree Days

For comparing the different climate scenarios and their possible impact on heating and cooling needs of the buildings, useful parameters are heating (HDD) and cooling degree days (CDD). They are defined as the daily temperature difference between a fixed comfort indoor temperature and the outdoor one (185). This value can be evaluated for all the days of a period, usually a month or the whole year, constituting a starting indicator for annual heating and cooling needs of the building. Heating and cooling degree days are calculated with the following equations:

$$HDD = \begin{cases} \dfrac{\sum_{h=1}^{24}(18 - T_{out_h})}{24}, & T_{out_h} < 18\,°C \\ 0, & T_{out_h} \geq 18\,°C \end{cases} \quad (4)$$

$$CDD = \begin{cases} 0, & T_{out} \leq 21\,°C \\ \dfrac{\sum_{h=1}^{24}(T_{out_h} - 21)}{24}, & T_{out} > 21\,°C \end{cases} \quad (5)$$

where h is the hour counter of the daily hours and $T_{out,h}$ is the hourly outdoor air temperature.

Reference temperatures for HDD and CDD are respectively set to 18 °C and 21 °C, as suggested by the study of Margarit Roset et al. on calculation of degree days in Catalunya (186).

3.2. Building model

The building selected for this study is a typical Catalan multifamily dwelling, built between 1940 and 1980, the period after the end of Spanish civil war. This typology is the most common in the region, constituting the 45.4% of the total building stock until 2012 (187). It is sited in an urban block between two streets of 10 m width, in the middle of two other buildings of the same height, facing other buildings. The main façades are south and north oriented, while the east and west oriented walls are looking at internal patios of 30 m^2 each or they are shared with neighboring buildings. The south-exposed façade is indicated as "principal" one of the building, while the north-exposed façade as "retro" one.

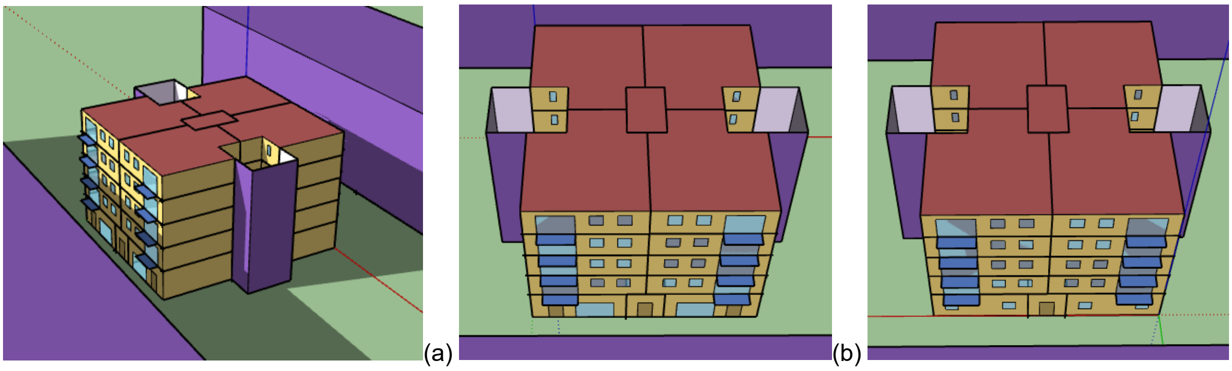


Figure 17: Views of the (a) total (b) south exposed facade (c) north exposed facade of the studied building

3.2.1. Geometry and Envelope characteristics

The building presents 4 floors above the ground, each one of them with 4 apartments with the same geometrical characteristics. On the ground floor there are some spaces, slightly smaller than the apartments above for the presence of two entrances, used as shops. In the center of the building stairs are present. Each space is considered a distinguished thermal zone, belonging to one category of apartments, shops and stairs&entrances. These three space categories have different geometric characteristics, occupancy schedules and loads. Resumes of the geometry are presented in the following tables:

	Floor Area [m^2]			Widow Area [m^2]			Volume [m^3]		
	Unit	Floor	Total	Unit	Floor	Total	Unit	Floor	Total
Apartments	80.10	320.40	1291.60	(2 m x 2.75 m) + 2x (1 m x 1 m) + (1 m x 0.5 m) = 8.00	32.00	128.00	200.25	801.00	3204.00
Shops	68.63	274.52	274.52	(3 m x 2 m) + (1 m x 0.5 m) = 6.5 or 2x (1 m x 1 m) + (1 m x 0.5 m) = 2.50	18.00	18.00	219.60	878.40	878.40
Stairs	15.00	15.00	75.00	0	0	0	37.50	37.50	198.00
Entrances	22.95	45.90	45.90	0	0	0	73.44	146.88	146.88
Total	-	**335.40**	**1677.00**	-	**50.00**	**146.00**	-	**1863.78**	**4427.28**

Table 4: Geometries of building spaces

	Total	North	East	South	West
Wall Area [m^2]	**765.60**	316.80	66.00	316.80	66.00
Window Area [m^2]	**146.00**	69.00	0.00	77.00	0.00
Window/Wall ratio [-]	**0.19**	0.22	0.00	0.24	0.00
Roof Area [m^2]	**335.4**	-	-	-	-

Table 5: Exterior surfaces summary

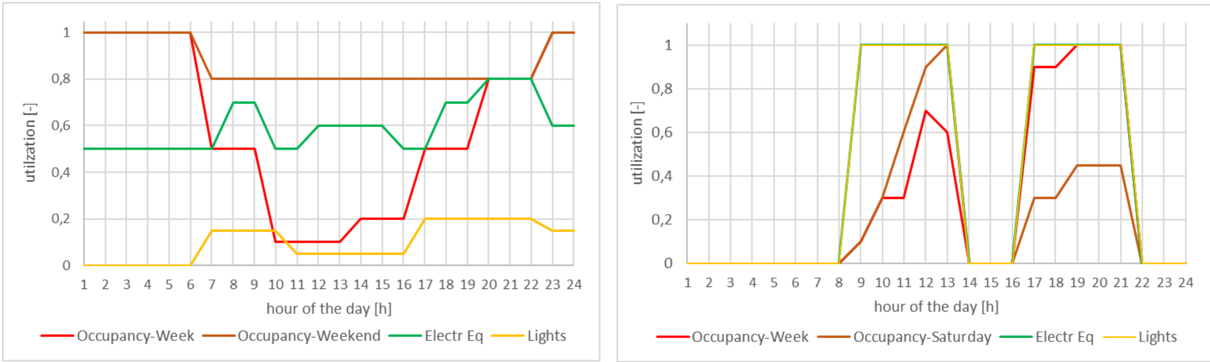
The envelope presents the original constructions, designed before the Spanish regulation of 1979 regarding minimum thermal requirements for buildings (188). The thermal properties of the different constructive elements are taken from the relative Spanish normative, as far as the methodology used for the calculation of thermal transmittance of the constructive elements (189) (190) (191) (192) (193).

Constructive element	Material	Thickness (cm)	Density [kg/m³]	Thermal Conductivity [W/m K]	Thermal Resistance [(m² K)/W]	Thermal transmittance [W/m² K]
Facades	External cement plastering	2	1800	1		**1.47**
	Perforated billet	14	1100	-	0.39	
	Air chamber	10		-	0.15	
	Drilled billet	4	1800	-	0.11	
	Plastered	1	1600	1	-	
Internal walls	Interior plastered	1	1600	1	-	**3.03**
	Perforated billet	14	1800	-	0.31	
	Interior plastered	1	1600	1	-	
Hollow slab between floors	Pavement	3	2300	1.3	-	**2.56**
	Floor screed	2	1800	1.15	-	
	Ceramic hollow slab	22	1800	-	0.34	
	Interior plastered	1	1600	1	-	
Roof	Ceramic tile floor	4	2300	1.3	-	**2.05**
	Asphalt fabric	0.5	2100	0.7	-	
	Cement layer	10	1800	1	-	
	Ceramic hollow slab	22	1800	-	0.34	
	Interior plastered	1	1600	1	-	
Facade openings	Steel frame	3	7800	50	-	**5.86**
	Single glass	0.4	2500	1	-	
Dividing wall	Perforated billet	14	1100	-	0.39	**2.50**
	Interior plastered	1	1600	1	-	

Table 6: Thermal properties and Transmittance of constructive elements of the building envelope

3.2.2. Schedules, Loads and Setpoint temperatures

Schedules and internal gains are defined for the different zones of the building. The two categories considered are residential apartments and shops, while stairs and entrances do not present any significant load or occupancy. Hourly trends of utilization are suggested from the relative Spanish normative (UNE-EN 16798-1, Parte 1) (194). Apartments follow the utilizations indicated in the normative, whereas for shops it is supposed that the working hours are from 8:00 and 13:00 and from 16:00 to 21:00 and the closing day is on Sunday. Schedules for occupancy, electrical equipment and lights are showed in the figures below:



(a) (b)

Figure 18: Schedules for occupancy, electrical equipment and lights inside (a) apartments (b) shops

Loads, like schedules, are dependent on the type of space and their values are suggested by normative. A table with values and ranges of values for occupancy, people activity, lights, electrical equipment and infiltrations, with the relative normative of reference, is present below (194) (195) (196) (197):

	Reference Normative	**Apartment values range**	**Shops values range**
Occupancy	UNE-EN 16798-1:2020	28.3 [m^2/person]	17.0 [m^2/person]
People Activity	UNE-EN ISO 8996:2021	100 – 150 [W/person]	170 [W/person]
Lights	DBHE 2022	1.0 [W/ m^2]	5.0 [W/ m^2]
Electrical Equipment	UNE-EN 16798-1:2020	3.0 [W/ m^2]	1.0 [W/ m^2]
Infiltrations	UNE-EN 16798-1:2020	0.5 [l/(s m^2)]	0.5 [l/(s m^2)]

Table 7: Reference normative and values ranges for loads of apartments and shops – values from (194) (196) (197)

Inside stairs and entrances only infiltrations are present, with the same value of 0.5 l/(s m^2) imposed for apartments and shops. This value is equal to the minimum ventilation rate imposed by UNE-EN 16798-1:2020 for residential facilities (194).

As final input of the building, setpoint temperatures for heating and cooling are imposed, shown in Table 8. These values are chosen on the basis of the ones recommended by UNE-EN 16798-1:2020 for residential and no-residential buildings (194). They are useful for evaluating energy needs of the facility and they are also used by some active cooling technologies as objective values. They are not imposed for stairs and entrances, since they are not climatized spaces.

	Heating	Cooling
Apartments	20 °C (8:30 – 22:00) 15 °C (nighttime)	26 °C (8:30 – 22:00) 28 °C (nighttime)
Shops	20 °C (8:00 – 21:00)	26 °C (8:00 – 21:00)

Table 8: Setpoint values for heating and cooling inside apartments and shops

It is important to notice that the cooling setpoint in apartments during nighttime is set to 28 °C for reasons regarding energy needs, that would result higher in case of maintenance of 26 °C also during night. Although, this nighttime setpoint in summer can cause thermal discomfort during some extremely hot periods, when operative temperature might exceed the comfort value. The same consideration is made for heating nighttime setpoint, set to 15 °C, that would decrease energy needs, but it could cause cold discomfort during the coldest periods of the year.

3.2.3. Simulation tool

For evaluating thermal conditions inside the building and its energy performance, considering dynamicity of outside conditions and effect of solar and internal gains, a model is created. The geometry is drawn in SketchUp, an open-source 3D and 2D modeling software, easy to use and able to simulate shadows during daily hours of the year (198). Apartments and shops are designed without internal partitions, considering that they will not significantly affect interior temperature, which is set at the same value in all the spaces. This software is easily connected to Energy Plus (EP), a building energy simulation program, that provides integrated heat balance-based solutions (199). The graphical interface used for it, that enables to set the input variables and to visualize the outputs easily, is OpenStudio (OS), widely used in the field of building simulations (200) (201). The results calculated by EP and presented by OS are exported and post processed using Microsoft Excel (202).

3.3. Cooling technologies

The aim of this work is to visualize the benefits of different cooling technologies on the resilience and energy needs and consumption of the existing building. From the large range of possible techniques, four passive and one active solution have been selected. These measures are implemented in the model, to simulate their behavior under different climatic conditions. Input parameters should be selected according to current regulations and recommendations regarding resilient cooling.

The implemented technologies and criteria for the choice of their respective input parameter are presented in this section.

Green roof (GrRf) does not have a proper regulation and minimum requirements to be satisfied. Considering its implementation on an existing building, roof thermal transmittance should not exceed the limit value of 0.40 W/m^{2}K, imposed by DBHE Ahorro de Energia (197). Although, this technology is not able to reduce alone transmittance until the imposed value, requiring the additional installation of an insulation layer in the roof. So, for evaluating the effect of only vegetation and soil, the maximum value of regulation should not be considered. This choice is not absolutely in contrast with DBHE, considering that plants and soil do not constitute a substantial modification of the building's cover. The different parameters of soil and leaf are chosen basing on the study of Zhou et al. (116), that simulated a green roof considering seasonal variation of leaf area index. In this work, LAI is set to the maximum possible value, equal to 5, since it provides the best performance during both winter and summer seasons (203).

Advanced solar shading (AdBl) implemented should satisfy the requirement of DBHE regarding solar control. Suggested reflectance values for blinds are provided by DA DBHE /1 (204), depending on the type of control and its color. In case of exterior shading control, solar reflectance should be higher than 0.2. In addition to this, it is important to define how it would be controlled. Advanced technologies allow to regulate in an automated manner the shading, depending on measured or set parameters (205) (206). In this model, advanced solar shading, more specifically blinds, are activated when interior temperature inside the apartments is greater than 25 °C. Additionally, the system modifies the slat angle of the blinds, in order to block the beam solar irradiation in the best way.

Advanced Glazing (AdWind) constitutes a substantial modification of openings, so it must accomplish the DBHE thermal transmittance limit of 2.1 W/m^{2}K. Regarding total solar factor and light transmittance, values are suggested by Zhang et al. (107), that in their critical assessment of resilient cooling technologies, indicated 0.3 as maximum value for the first and 0.6 as minimum one for the second. For simulating in a more accurate way this technology, a real window, available in the market, is considered. The selected one is the COOL-LITE® XTREME 61/29 (II) of Saint-Gobain Building Glass (207).

Natural ventilative cooling (NV) is strongly dependent on the location where it is implemented. It is function of wind and temperatures, that create pressure differences between inside and outside spaces (129). Pressure distributions depend on the shape of the building, wind speed and direction and surroundings of the building, like upstream terrain and other constructions (130). For this work, ventilation rate is supposed to have a fixed value of 4 ach. This number is chosen basing on the study of Ortiz et al. (208) regarding impact of natural ventilative cooling in a residential building in Catalonia, of the same typology of the one investigated in this thesis. Some constraints are imposed for its use, relative to outdoor and indoor temperatures. Ventilation is activated when indoor temperature is higher than 25 °C and at least 1°C higher than the outdoor one, for guaranteeing its cooling effect.

Vapor compression refrigeration (AC) used is composed of an air unitary single speed DX system, connected with a single duct diffuser and an outdoor air system (209). All these components are already implemented in OpenStudio and it is possible to edit their characteristics. Each thermal zone is equipped with its proper AC unit, to have a major control of the parameters and consumption of the system. They are singularly sized during the summer day of project of each time scenario, supposing to substitute the system in according to its lifetime and different climate conditions (210). Considering that creation of days of project for sizing the thermal equipment is not a part of this work, the day with the higher temperature of each TMY is used as day of project. In this way, it is possible to evaluate the stress caused by unexpected extreme weather on this technology and, consequently, on the indoor environment.

For practical reasons related to their actions and effects, in this work passive solutions and active solutions are also referred by the category defined by Annex 80 and presented in Table 2. It is reminded that the ones that contributes to the reduction of external gains to the indoor environment are in Category A, while the ones that remove heat from the indoor environment are in Category B (43) (107). In this way, green roof, advanced solar shading and advanced glazing, recognized as passive measures, are in Category A, while natural ventilative cooling, that is also a passive technology, and vapor compression refrigeration, that is an active one, are in Category B.

The set parameters of each measure are shown in Table 9.

Technology	Parameter	Unit	Value	Schedules
Green Roof (GrRf)	Height of Plants	m	0.2	-
	Leaf Area Index	-	5.0	
	Leaf Reflectivity	-	0.22	
	Leaf Emissivity	-	0.95	
	Minimum Stomatal Resistance	s/m	180	
	Soil Thickness	m	0.1	
	Conductivity of Dry Soil	W/(m K)	0.35	
	Density of Dry Soil	kg/m^3	1100	
	Specific Heat of Dry Soil	J/(kg K)	1200	
Advanced Solar Shading (AdBl)	Slat Width	m	0.025	Minimum Indoor Temperature: 25 °C Slat Angle: depending on solar beam irradiation
	Slat Separation	m	0.019	
	Slat Thickness	m	0.010	
	Slat Angle	deg	variable	
	Slat Conductiovity	W/(m K)	221	
	Slat Solar Reflectance	-	0.32	
	Slat Infrared Hemispherical Emissivity	-	0.68	
	Blind to Glass Distance	m	0.05	
Advanced Glazing (AdWind)	U-value	$W/(m^2 K)$	1	-
	Solar Heat Gain Coefficient	-	0.29	
	Visible Transmittance	-	0.61	
Natural Ventilative Cooling (NV)	Air Changes per Hour	1/h	4	Minimum Indoor Temperature: 25 °C Delta Temperature: 1 °C
Vapor Compression Refrigeration (AC)	Supply Air Flow Rate	m^3/s	Sized on ddy	Always On when required Load control based on setpoint temperature
	Rated Total Cooling Capacity	W	Sized on ddy	
	COP	-	3	

Table 9: Input parameters of cooling technologies

3.4. Resilience and performances indicators

For evaluating the condition inside the building and other different parameters, it is necessary to define some indicators useful for the analysis. They are selected from previous studies on resilience and indoor overheating, or from Spanish normative and regulation (146) (149) (150) (211) (154) (155) (212).

3.4.1. Climate resistance indicators

Resilience indicators used in this work are the ones presented in the study of Hamdy et al. (146).

Indoor overheating degree (IOD) quantifies the overheating risk inside a building, considering intensity and frequency of indoor overheating. It is able to take into account different comfort limits, occupancy and conditions of each zone. Intensity is quantified by the positive differences between operative temperature T_{op} and a chosen thermal comfort temperature limit T_{comf}, while frequency is considered integrating overheating along the occupied period of the different zone. Equation of IOD is proposed below:

$$IOD = \frac{\sum_{z=1}^{Z} \sum_{i=1}^{N_{occ}(z)} \left[\left(T_{op_{,i,z}} - T_{comf_{,i,z}} \right)^{+} \cdot t_{i,z} \right]}{\sum_{z=1}^{Z} \sum_{i=1}^{N_{occ}(z)} t_{i,z}} \quad (6)$$

where z is the building zone counter, i is the occupied hour counter, t is the time step, Z is the total number of zone in the building, $N_{occ}(z)$ are the total occupied hours, $T_{op,i,z}$ is operative temperature inside the zone during the occupied hour and $T_{comf,i,z}$ is the comfort temperature of the zone during the occupied hour.

For this study, $T_{comf,i,z}$ is set to 26 °C, temperature chosen considering category II of comfort in residential building during summer operation, with sedentary activity of 1.2 met and clothing insulation of 0.5 clo, proposed by the Spanish normative UNE-EN ISO 16798-1 (194).

Ambient warmness degree (AWD) evaluates severity of outside warmness conditions, respect to a base temperature, related to summer comfort limits. This indicator is very useful for quantifying changes in climatic scenarios along different periods and events. Equation of AWD is the following one:

$$AWD_{18\,°C} = \frac{\sum_{i=1}^{N_{occm}} [\left(T_{a,i} - T_b \right)^{+} \cdot t_i}{\sum_{i=1}^{N_{occm}} t_i} \quad (7)$$

where $T_{a,i}$ is outdoor air temperature at the time i, T_b is a reference outside temperature, t is the time step, $N_{occ,m}$ is the maximum number of occupied hours during the selected period. Reference temperature T_b is set to the value of 18 °C, that is the temperature recommended by the creators of these indicators (146).

Overheating escalation factor (α) is a parameter that estimates the sensitivity of overheating risk inside building zones, caused by severe outdoor conditions. Assuming that the relationship between IOD and AWD can be represented with a linear regression model, this factor would be the slope coefficient of the regression line. It is defined as:

$$\alpha = \frac{IOD}{AWD_{18\,°C}} \quad (8)$$

If the overheating escalation factor is greater than 1, it means that the building is not able to resist outside conditions, since indoor overheating obtained is higher than outdoor warmth severity. Whereas, if the factor is lower than 1, the dwelling is able to contrast outdoor thermal stress.

3.4.2. Comfort indicators

Degree weighted discomfort hours (DDH) correspond to the number of hours during a considered period when operative temperature exceeds a hot or cold threshold, weighted by a factor dependent on by how many degrees the reference temperature has been exceeded. This indicator is used for buildings without mechanical conditioning systems. The methodology for calculating the DDH is presented in the Annex D of the standard UNE-CEN/TR 16798-2:2019 (213). The two thresholds are selected basing on adaptive criteria (194) (214), presented in Annex B, chapter B.2.2 of the standard UNE-EN 16798-1:2020 (194), during the summer and intermediate seasons, and recommended design values of indoor operative temperature in winter for buildings with mechanical cooling systems in the Annex B, table B.2 of the same standard (194), during winter. In particular, category III of comfort was selected, supposing the progressive adaptation of people inside the buildings during new average climatic conditions and frequent and severe heatwaves in the future. Temperature thresholds according to adaptive criteria is calculated with the following equation:

$$upper\ limit\ \ T_{op,up} = 0.33\ \cdot\ \theta_{rm} + 18.8 + 4 \quad (9)$$

$$lower\ limit\ \ T_{op,low} = 0.33\ \cdot\ \theta_{rm} + 18.8 - 5 \quad (10)$$

Where θ_{rm} is the running mean outdoor temperature, evaluated with the equation:

$$\theta_{rm} = \frac{\theta_{ed-1} + 0.8 \cdot \theta_{ed-2} + 0.6 \cdot \theta_{ed-3} + 0.5 \cdot \theta_{ed-4} + 0.4 \cdot \theta_{ed-5} + 0.3 \cdot \theta_{ed-6} + 0.2 \cdot \theta_{ed-7}}{3.8} \quad (11)$$

With θ_{ed-i} is the daily mean temperature of outdoor air of the i-th previous day.

This adaptive model is valid for 10 °C < θ_{rm} < 30 °C. For values of θ_{rm} higher than 30 °C, the comfort threshold is set to 32.7 °C, that corresponds to the upper limit in case of θ_{rm} equal to 30 °C. When θ_{rm} is lower than 10 °C, for example during winter season, the lower limit is set to 18 °C.

Cold Degree weighted discomfort hours (CDDH) and Hot Degree weighted discomfort hours (HDDH) are defined as:

$$CDDH = \sum_{z=1}^{Z} \left(T_{op,low} - T_{op_z} \right) \cdot occ_{z,i} \;\; for\, T_{op_z} < \; T_{op,low} \; (12)$$

$$HDDH = \sum_{z=1}^{Z} \left(T_{op_z} - \; T_{op,up} \right) \cdot occ_{z,i} \;\; for\, T_{op_z} > \; T_{op,up} (13)$$

with $$occ_{z,i} = \begin{cases} 0, & occupancy_{z,i} < 1 \\ 1, & occupancy_{z,i} \geq 1 \end{cases}$$

where z is the zone counter, Z is the total number of zones, i is the occupied hour counter.

PPD weighted discomfort hours (PDH) correspond to the number of hours during a considered period when PMV exceed the comfort boundaries, weighted by a factor dependent on the correspondent PPD. PMV (Predicted Mean Vote) and PPD (Predicted Percentage Dissatisfied) are based on Fanger’s comfort model (215), calculated according to the ISO 7730 (216). This indicator is used for buildings with mechanical conditioning systems. The methodology for calculating the DDH is presented in the Annex D of the standard UNE-CEN/TR 16798-2:2019 (213). The PMV and PPD thresholds are set according to comfort categories for mechanical conditioned buildings, presented in Annex B, table B.1 of the standard UNE-EN 16798-1:2020 (194). Also in this case, the comfort category that has been selected is Category III. Acceptable PMV values, for the selected category, should stay in the range -0.7 < PMV < +0.7. Acceptable PPD values, for the selected category, should not exceed 15%.

Cold PPD weighted discomfort hours (CPDH) and Hot PPD weighted discomfort hours (HPDH) are defined as:

$$CPDH = \sum_{z=1}^{Z} \left(\frac{PPD_{PMV_z}}{PPD_{PMV_{low}}} \right) \cdot occ_{z,i} \;\; for\, PMV_z < \; PMV_{low} \; (14)$$

$$HPDH = \sum_{z=1}^{Z} \left(\frac{PPD_{PMV_z}}{PPD_{PMV_{up}}} \right) \cdot occ_{z,i} \;\; for\, PMV_z > \; PMV_{up} \; (15)$$

with $$occ_{z,i} = \begin{cases} 0, & occupancy_{z,i} < 1 \\ 1, & occupancy_{z,i} \geq 1 \end{cases}$$

where z is the zone counter, Z is the total number of zones, i is the occupied hour counter, PMV_z is the PMV for the considered zone and time, PPD_{PMV_z} is the correspondent PPD for the PMV_z,

PMV_{low} and PMV_{up} are the lower and upper PMV limit for the selected comfort category, $PPD_{PMV_{low}}$ and $PPD_{PMV_{up}}$ are the correspondent PPD for PMV_{low} and PMV_{up}.

Heat Index (HI) is a widely used indicator in the USA, representing the human feeling in response to air temperature and relative humidity. It is the result of multiple regression analysis of Lans P. Rothfusz (138), presented in 1990 National Weather Service (NWS) Technical Attachment (SR 90-23) (217). This index is useful to detect discomfort and possible strokes caused by warm conditions. There are four main levels of danger related to heat stress, detected with HI, presented in Table 10. These levels are used only for hot events and they are calibrated on general population. It is defined as:

$$HI = c_1 + c_2 T + c_3 RH + c_4 TRH + c_5 T^2 + c_6 RH^2 + c_7 T^2 RH + c_8 TRH^2 + c_9 T^2 RH^2 \quad (16)$$

c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9
-8.78469475	1.61139411	2.33854884	-0.14611605	-0.01230809	-0.01642483	0.00221173	0.00072546	-0.00000358

where T is air temperature expressed in Celsius [°C] and RH is percentual relative humidity [%].

If HI < 26.7 °C, equation is simplified:

$$HI = 1.1\,T + 0.0261\,RH - 3.94 \quad (17)$$

HI Range	**Hazard Category**	**Heat Syndrome**
< 27 °C	Safe Conditions	None
27 – 32 °C	Caution	Fatigue possible with prolonged exposure and physical activity
32 – 41 °C	Extreme Caution	Sunstroke, heat cramps, and heat exhaustion possible with prolonged exposure and physical activity
41 – 54 °C	Danger	Sunstroke, heat cramps, or heat exhaustion likely. Heat stroke possible with prolonged exposure and physical activity
> 54 °C	Extreme Danger	Heatstroke or sunstroke imminent

Table 10: Hazard category related to HI levels

3.4.3. Environmental impact and costs indicators

In this work different time scenarios are used and analyzed, for evaluating needs and consumptions of the building along the years and the effects of climate change on them. For this reason, whenever aspects external to the building system are considered, it is essential to adequate their parameters in accordance with real or predicted characteristics of the selected scenario.

3.4.3.1. Primary Energy conversion and CO_2 emissions factors

The first parameter that is evaluated is the amount of primary energy that should be used for producing electricity required by vapor compression refrigeration in the apartments and shops. Primary energy (PE) is defined as "the amount of energy found in nature, like raw fuels or waste, used as input to a system" (218) (219). It is very useful for comparing different types of energy and it is widely used for studies on energy efficiency, statistics and balances (219). This magnitude is calculated from electric consumption using conversion factors, specific for each type of energy and context (220). In Spain, values useful for residential buildings are present in the document "Factores de Emisión de CO2 y Coeficientes de Paso a Energía Primaria ", recognized from the Reglamento de Instalaciones Térmicas en los Edificios (RITE) (212), where coefficients are differentiated for zone and typology of energy. For this work, the factor of conversion considered is the one for electric energy, that is function of the contribution of each power source to the total national electrical generation and the factor of conversion of each of them.

In the Present scenario, this value is taken from this regulation. Indeed, for the Mid Future, it is preferable to calculate it, basing on the most probable configurations of electrical generation during those years. Unfortunately, there are no plans or previsions available for a such distant period. However, Spain government has developed a plan for reducing emissions and improving sustainable generation and use of energy (221). According to it, Spain declares the objective of generating 74% of its electrical production from renewable energy sources by 2030. Two forecasts of share of the different sources in generation are made, one according to the proposed objective and the other predicting the most probable scenario that would be present for that date. Objective scenario is quite difficult to be achieved by 2030, but it is very probable to be obtained in 2050. From this prevision, the objective scenario of the Energy Plan is used in this work for representing the generation of electricity in Spain during the Mid Future period. For the Long Future there are any other previsions and making them would be unreasonable and almost impossible. For these reasons, the amount of primary energy and carbon emissions would not be evaluated for this scenario. Percentages of the different energy source in this configuration are presented in Table 12.

Primary energy conversion factor for electricity is calculated averaging the primary energy factors of the different sources, weighting them on their respective contribution to electric generation. Single factor of each technology is calculated from the values obtained for the different years from 2005 to

2013, present in the document of RITE (212). Averaging these values, it is possible to obtain the single PE factor of each source.

Factors for each year and source are shown in Table 11.

	Primary Energy factors for each year								
Energy Source	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**
Nuclear	3.665	3.661	3.661	3.654	3.647	3.639	3.647	3.651	3.649
Carbon	3.189	3.257	3.23	3.116	3.154	3.23	3.341	3.265	3.085
Combined Cycle	1.924	2.043	1.928	1.963	2.02	2.146	2.116	2.372	2.284
Hydro	1.027	1.047	1.078	1.076	1.087	1.116	1.119	1.024	1.078
Wind	1.599	1.724	1.689	1.631	1.479	1.458	1.515	1.639	1.473
Solar FV	1.599	1.724	1.689	1.631	1.479	1.458	1.515	1.639	1.473
Solar Th	1.599	1.724	1.689	1.631	1.479	1.458	1.515	1.639	1.473
Biomas	1.599	1.724	1.689	1.631	1.479	1.458	1.515	1.639	1.473
Cogeneration	1.599	1.724	1.689	1.631	1.479	1.458	1.515	1.639	1.473

Table 11: Primary Energy factors for each source and year – rearranged from (67)

The second variable to be evaluated is the amount of CO_2 emissions related to electricity consumption of vapor compression refrigeration of the building. Also in this case, the factor of emissions is dependent on the scenario of production, since it is function of the different energy sources. For the Present, emission factor is taken from the regulation of 2021, “Emisiones de CO2 asociadas a la generación de electricidad” (222). For Mid Future, the factor is calculated, basing on the predicted configuration of electric generation, averaging emission factors of all the sources, provided by the cited regulation of 2021 (222).

A table with the contribution of each source to total electric production in peninsular Spain, PE factors and emission factors for Mid future periods is the following:

2030 Objective Scenario (used for Mid Future Scenario)			
Energy Source	**contribution in total electricity production [%]**	**PE factor [kWh/kWh]**	**CO2 emission factor [tCO2-eq/MWh]**
Nuclear	7.2	3.65	6.80E-03
Carbon	0.00	3.21	0.95
Combined Cycle	9.00	2.09	0.37
Hydro	10.50	1.07	0.00
Wind	35.70	1.58	0.00
Solar FV	21.20	1.58	0.00
Solar Th	6.40	1.58	0.00
Residues	3.90	1.58	0.12
Cogeneration	6.00	1.58	0.38

Table 12: Contribution in Electricity Production, PE factor and emission factor for each source in Mid Future – rearranged from (67), (78) and (79)

Final equations for calculations of PE and CO_2 emissions factors are the following:

$$PE\ factor = \sum_{s=1}^{S} \frac{cp_s}{100} \cdot \frac{\sum_{y=1}^{Y} PE\ factor_{y,s}}{Y} \quad (14)$$

With s the counter of the energy sources, S the total number of energy sources, cp_s the percentual contribution of the single source in the total electricity production, y the counter of the years and Y the total number of years.

$$CO_2\ emission\ factor = \sum_{s=1}^{S} \frac{cp_s}{100} \cdot CO_2\ emission\ factor_s \quad (15)$$

With s the counter of the energy sources, S the total number of energy sources and cp_s the percentual contribution of the single source in the total electricity production.

3.4.3.2. Electricity Price estimation

The last aspect investigated is the economic savings provided by implementation of different passive technologies. It is function of electricity price, costs of installation and costs of maintenance of each measure. Although, in this study only the savings on energy bills will be evaluated.

Electricity price is a very variable parameter, depending on several factors like fuel cost, power plant costs and availability, period of the year, hour of the day, weather conditions, trends of other markets and geographic location and state regulations (223). Prediction of possible prices is very difficult for the Present, almost impossible for Mid Future and absolutely unreasonable for Long Future. Although, some considerations and hypotheses can be made for its evaluation.

For the Present, that occurs from 2006 and 2025, electricity price is calculated basing on historical values of the period between 2012 and 2022. Values for Spain are provided by OMIE, according to their annual reports for each year of the selected range (224). Annual values are used for savings during TMY, whereas, for HWs, the price is calculated making some additional considerations. In fact, according to the study of Pechan and Eisenack (225) made for the 2006 heatwave in Germany, electricity prices during HWs increases by 4%.

For each year between 2012 and 2022, annual electricity price is taken from the reports of OMIE, while summer HWs price is calculated averaging the prices of the summer months, from June to September, increasing the obtained value of 4% (224). A table with the different annual, summer HWs and summer months prices of each year of the considered period is presented below.

Year	Annual Price [€/MWh]	Summer HWs Price [€/MWh]	Summer Price [€/MWh]	Summer HWs Variation [€/MWh]	June Price [€/MWh]	July Price [€/MWh]	August Price [€/MWh]	September Price [€/MWh]
2012	47.2	52.8	50.8	2.0	54.0	50.5	49.5	49.0
2013	44.3	49.0	47.1	1.9	40.5	51.0	47.0	50.0
2014	42.1	54.7	52.6	2.1	51.5	48.5	51.0	59.5
2015	50.3	57.7	55.5	2.2	54.7	59.6	55.6	51.9
2016	39.7	42.7	41.1	1.6	38.9	40.5	41.2	43.6
2017	52.2	50.8	48.9	2.0	50.2	48.6	47.5	49.2
2018	57.3	66.6	64.0	2.6	58.5	61.9	64.3	71.3
2019	47.7	48.4	46.6	1.9	47.2	52.0	45.0	42.1
2020	34.0	37.3	35.9	1.4	30.6	34.6	36.2	42.0
2021	111.9	113.9	109.5	4.4	83.3	92.4	106.0	156.2
2022	167.5	158.2	152.1	6.1	169.6	142.7	154.9	141.1

Table 13: Electricity Prices in 2012-2022 period – rearranged and modified from (81)

Letterly, these annual and summer HWs prices are averaged, finding singular values for them.

For the assessment of electricity price during Mid Future scenarios, the estimated variable cost of generation, proposed in the "Plan Nacional Integrado De Energía y Clima 2021-2030" (221), is considered. Also in this case, the price for heatwave period is majored of 4%. The price of electricity in Long Future scenario has not been considered in this analysis for the difficulties on its evaluation.

3.5. Studied scenarios

Resilience and performances of technologies are tested along different scenarios. This allows to evaluate in a complete way their performance both during extreme events and normal conditions. In addition, climate modification caused by human activities are considered, extending the proposed analysis to future years. This would significantly help the research on cooling techniques, predicting which ones would be more efficient in case of new weather conditions and opening to possible strategies to adopt.

Technologies are tested alone and combined, whenever possible. The first configuration is important for understanding the strengths and weaknesses of each one, while the second is useful in view of real implementation, optimizing thermal conditions and energy consumption.

3.5.1. Typical Meteorological Year (TMY)

Analysis conducted during TMY is important for evaluating the benefits of technologies on energy needs and consumptions of the building. Both heating and cooling needs are considered, since some of these techniques are fixed in the envelope, with the possibility of badly affecting heating needs. In case of vapor compression refrigeration implementation, electricity consumptions and the associated environmental and cost impact are investigated, understanding how passive measures could bring benefits to the customers and to the environment. Resilience is also analyzed during these typical years, for assessing response of the building to new average outdoor conditions, that could be also very different from the ones present during its design. It should be mentioned that IOD, AWD and α were originally created for analyzing only summer periods. For this reason, evaluating them during the whole year can produce results that are not in accordance with the typical ranges calculated in case of shorter and warmer periods.

3.5.2. Heatwaves (HWs)

The concept of resilience is strictly correlated to the presence of extreme events that cause failures in the system. The most common example of these events are heatwaves. At first, their impact on resilience, energy needs and consumption of the original building is evaluated, understanding the severity of these phenomena on the existing built environment. Then, the attention is moved to the improvement provided by cooling technologies on its resilience. Finally, their contribution to the reduction of consumption and environmental and cost impacts, during heatwaves with the highest AWD in each time period, is assessed. It is important to highlight the impossibility to implement natural ventilative cooling during heatwaves of Long Future scenario, caused by minimum outside temperatures always higher than the NV availability threshold of 26 °C.

3.5.3. Power outages (PO)

The last type of disrupting event investigated is power outages (PO). These events likely occur during heatwave periods, caused by continuative use of active cooling systems, that significantly increase electricity demand (93). Power outages depends on the structure and the reliability of electric grid, but also on the characteristics of the urban environment and its citizens (226). For these reasons, it is difficult to predict their occurrence and duration. In fact, there is a small number of publications regarding them in the ambit of energy building simulations and absence of a standard methodology for simulating them. In this work, in order to be conservative, it is supposed that PO would occur for the whole period covered by a HW. For reason related to the duration and severity of the HW, only PO occurring during the HW with the highest value of AWD between the ones selected for the three time periods are investigated.

For understanding better the breakdown and recovery effects lead to the different cooling technologies, simulations are run starting from five days before the beginning of the selected HW and finishing five days after.

In the following table, the days selected for PO of each time period are shown:

	Simulated Period	PO Period
Present Most Severe HW	15/07 - 31/07	20/07 - 26/07
Mid Future Most Intense&Severe HW	26/07 - 13/08	31/07 - 08/08
Long Future Most Intense HW	28/08 - 13/09	02/09 - 08/09

Table 14: Day selected for PO during the HW of each time period

A final resume of all the different implemented technologies, simulated scenarios and evaluated parameters, is presented in Table 15.

x: Resilience +: Energy Needs /: Electr. Consumption	TMY Present	TMY Mid Future	TMY Long Future	Heatwaves Present Longest	Heatwaves Present Most Intense	Heatwaves Present Most Severe	Heatwaves Mid Future Longest	Heatwaves Mid Future Most Intense & Severe	Heatwaves Long Future Longest & Most Severe	Heatwaves Long Future Most Intense	Power Outages Present Most Severe	Power Outages Mid Future Most Intense & Severe	Power Outages Long Future Most Intense
Base Case	x +	x +	x +	x +	x +	x +	x +	x +	x +	x +			
GrRf	x +	x +	x +	x	x	x	x	x	x	x			
AdBl	x +	x +	x +	x	x	x	x	x	x	x			
AdWind	x +	x +	x +	x	x	x	x	x	x	x			
GrRf+AdBl	x +	x +	x +	x	x	x	x	x	x	x			
GrRf+AdBl+AdWind	x +	x +	x +	x	x	x	x	x	x	x			
NV	x +	x +	x +	x	x	x	x	x					
GrRf+NV	x +	x +	x +	x	x	x	x	x					
AdBl+NV	x +	x +	x +	x	x	x	x	x					
AdWind+NV	x +	x +	x +	x	x	x	x	x					
GrRf+AdBl+NV	x +	x +	x +	x	x	x	x	x					
GrRf+AdBl+AdWind+NV	x +	x +	x +	x	x	x	x	x					
AC	x /	x /	x /	x	x	x /	x	x /	x	x /	x	x	x
GrRf+AC	x /	x /	x /	x	x	x /	x	x /	x	x /	x	x	x
AdBl+AC	x /	x /	x /	x	x	x /	x	x /	x	x /	x	x	x
AdWind+AC	x /	x /	x /	x	x	x /	x	x /	x	x /	x	x	x
GrRf+AdBl+AC	x /	x /	x /	x	x	x /	x	x /	x	x /	x	x	x
GrRf+AdBl+AdWind+AC	x /	x /	x /	x	x	x /	x	x /	x	x /	x	x	x

Table 15: Implemented technologies, simulated scenarios and evaluated parameters

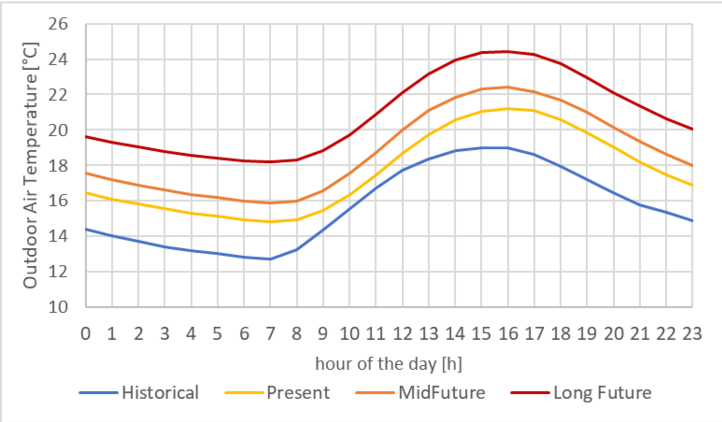
4. Results of weather data creation

Following the methodology proposed by the Weather Task Force of Annex 80 (156), weather files of TMY and HWs have been created. In this chapter the data of the different time periods are compared, to have a view of the possible impact of climate change on the city of Barcelona.

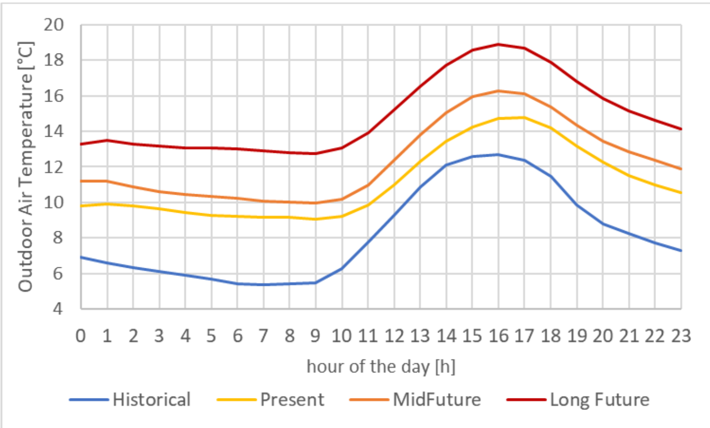
4.1. TMY

For the TMY comparisons are made on the average annual temperature and on the ones of heating and cooling season.

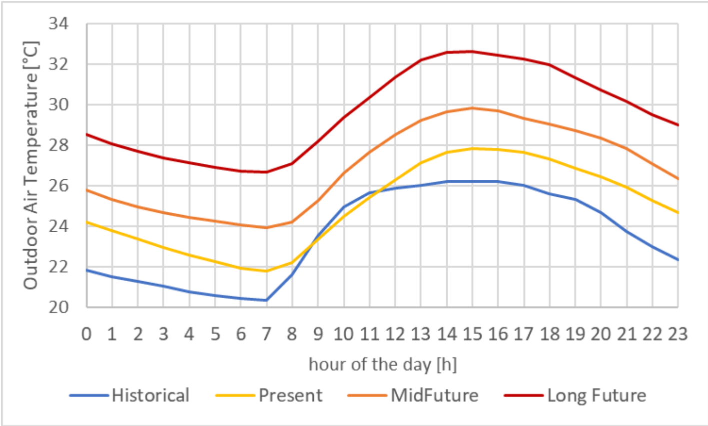
The following figures are show the daily annual and the daily January and July temperatures of the Present, Mid Future and Long Future scenarios. Historical temperatures are also considered, to have a complete view of the climate change phenomenon.



(a)



(b)



(c)

Figure 19: Daily (a) annual (b) January (c) July outdoor air temperature during the different time periods

From Figure 19 it is evident how human activities and the related GHG emissions would impact on the average temperatures of the year. Temperatures of the Long Future scenario result much higher than the historical and Present ones, because of the effect of continuous emissions in the atmosphere, simulated in the RCP8.5 scenario. Its incrementations respect to Historical, Present and Mid Future scenario are approximately equal to 5 °C, 3 °C and 2 °C. Differences between each scenario become more evident during January and July, especially for the future scenarios.

For evaluating the possible impact on needs of buildings, heating and cooling degree days are calculated. Both annual and monthly degree days are considered. The results are shown in the following plots:

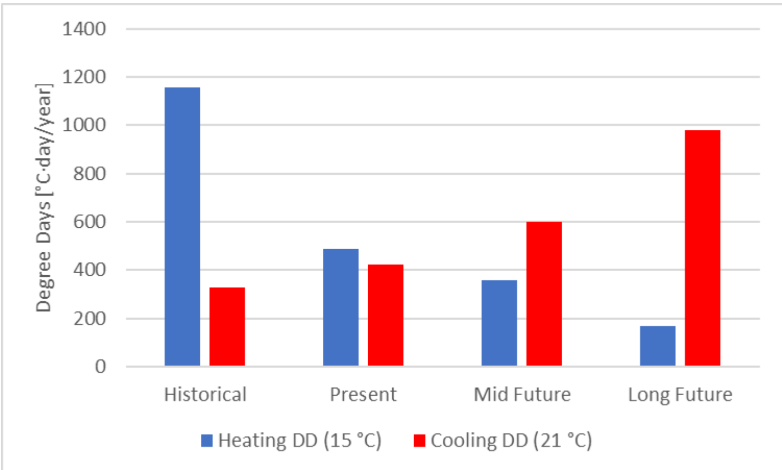


Figure 20: Annual heating and cooling degree days of the different time periods

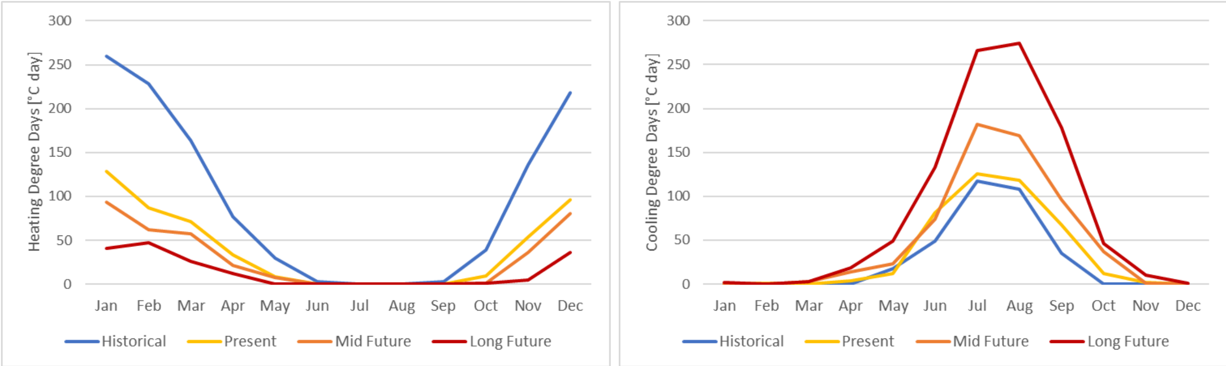


Figure 21: Heating and Cooling Monthly Degree Days of the different time periods

Degree days show a substantial modification of the heating and cooling needs of buildings moving through the years. In the historical scenario, heating need is much higher than the cooling one. Its HDD present significant values not only during winter, but also in autumn, while CDD are important only during summer. On the other hand, in the Present and Mid Future scenario, periods of demand are almost equal, being heating and cooling seasons respectively reduced and increased by two months compared to historical ones. HDD and CDD result almost equal in the Present, while the seconds start to be dominant in Mid Future. The situation during Long Future is almost reversed compared to the Historical scenario. CDD are significatively higher than HDD. The heating monthly ones never exceed the value of 50 °C·day and they are present only between November and April. At the same time, CDD result much higher than the ones of Historical Present and Mid Future scenarios, especially during summer months.

4.2. HWs

For comparing the different heatwaves, the same parameters used for the definition of the most representative heatwaves of each time period are calculated. They are maximum daily mean temperature, severity and duration. A table resuming the found HWs, with the relative parameters, is shown below:

HW Scenario		Max Daily Tmean [°C]	Severity [C·hours]	Duration [days]	Beginning of HW	End of HW
Present	Longest	28.40	6.80	13	2013-08-24	2013-09-05
	Most Intense	30.10	8.20	9	2017-08-09	2017-08-17
	Most Severe	30.00	10.80	7	2021-07-20	2021-07-26
Mid Future	Longest	30.30	7.50	12	2058-07-22	2058-08-02
	Most Intense & Most Severe	31.40	11.90	9	2060-07-31	2060-08-08
Long Future	Longest & Most Severe	33.90	20.40	36	2084-07-13	2084-08-17
	Most Intense	34.60	8.20	7	2099-09-02	2099-09-08

Table 16: Most representative heatwaves and relative parameters of the different time periods

It is important to highlight how heatwaves become potentially more dangerous in the future. All the parameters increase moving through the years, especially maximum daily mean temperatures and severity. Duration remains almost the same for all the periods, except for the Longest and Most Severe heatwave of Long Future scenario, that exceeds the duration of a month. This last heatwave also presents a very high severity, confirming the dangerousness of these events during the future years.

5. Results of resilience analysis

After preliminary considerations on characteristics of created weather data and their impact on the original building, it is possible to test the different cooling technologies, assessing their performance during the whole year and in case of extreme events.

5.1. Base case

First of all, it is important to define the starting point of the study, evaluating the performance of the building as it is presented, without any cooling technology implemented. It is recommended to test it in every climatic scenario, along the years, to understand how climate change would affect comfort and energy request. Analyzing thermal conditions inside the different spaces, it is possible to highlight which zones are the most critical and the different parameters that contribute to the obtainment of determined conditions.

5.1.1. TMY

As first thing, building behavior during common climate conditions is investigated.

5.1.1.1. Energy needs

Even if any thermal equipment is present in the building, it is possible to evaluate the hypothetical thermal needs that would be required from the system, to maintain the selected set-point temperatures during the year. For this parameter, results are compared with the ones obtained using historical weather data. Heating, cooling and total needs of each scenario and the relative percentual variation compared to the Historical ones are presented in the following table. In addition, the ratio between cooling and heating needs is evaluated.

	Heating Need [kWh/m$^2_{cond}$]	Cooling Need [kWh/m$^2_{cond}$]	Total Needs [kWh/m$^2_{cond}$]	Cooling/Heating [-]
Historical	27.41	12.6	40.37	0.47
Present 2006-25	11.81 (-56.91%)	21.58 (+66.51%)	33.39 (-17.29%)	1.83
Mid Future 2041-60	8.52 (-68.92%)	30.25 (+133.41%)	38.77 (-3.96%)	3.55
Long Future 2081-100	2.89 (-89.46%)	49.73 (+306.02%)	52.62 (+30.34%)	17.21

Table 17: Energy Needs and Percentual Variation from Historical scenario during TMY in Base Case

From Table 17 it is possible to notice how future climate change would affect energy requests during an average year. Moving through the years, heating need reduces, whereas cooling need increases.

From the Present scenario, variation for heating is significant, whereas cooling need increases considerably in the others, as noticed from the relative increment of 133% and 306%, respect to the historical one. These results are in accordance with the ones found by Pourabdollahtootkaboni for buildings in Italy (148). A crucial indicator for the evaluation of this trend is the division between cooling and heating needs. In the historical scenario, this number is lower than 1, around 0.5, being heating need higher than the cooling one. In the new scenarios, this value reverses, settling, respectively, around 2, 4 and 17 for present, mid future and long future. These numbers, especially the last one, highlight how the use of new weather data can help on the design of new buildings and their equipment, on the requalification of the built environment and on the review of legislation about minimum requirements and design conditions for residential and non-residential constructions.

Total energy needs for conditioning increases along the new scenarios, but it is higher than the historical one only in the Long Future. This result could be seen as positive for the near future, but it should be reminded that, most of the time, heating and cooling devices have different characteristics, so the correct comparison should be conducted in terms of energy and primary energy consumption.

5.1.1.2. Climate resistance assessment

An important aspect to be investigated is the resistance of the building to the new climate. This evaluation is made with the three indicators IOD, AWD and α, presented in chapter 3.4.1. As mentioned before, they provide a more adequate analysis during extreme scenarios, such as heatwaves, but the investigation on a full-year period can help to understand the reaction of the building to average flexibility of temperatures during a common year.
The results of this study are presented in Table 18:

	IOD	AWD	**α**
Present	1.14	2.21	**0.52**
Mid Future	1.57	2.80	**0.56**
Long Future	2.41	4.06	**0.60**

Table 18: Resilience indicators during TMY in Base Case

The first parameter to be investigated is the IOD. For the three scenarios, values achieved are, in order of time, around 1 °C, 1.5 °C and 2 °C. It means that, averaging the total occupied hours of the year, temperatures are higher than the one recommended for summer comfort. It should be remembered that these are annual values, calculated on the annual occupied hours, so it means that overheating inside the building during the hottest periods of the year can be much higher than the IOD value.

The second indicator analyzed is the AWD. It detects modifications of average outdoor temperature during occupied hours of the year. Incrementations are equal to 2.2 °C in the Present scenario, arriving to 4.1 °C in the Long Future one. This incremental trend through the years quantifies the actual and the future possible modifications caused by human emissions.

Climate resistance of the building is assessed with the escalation factor α. For all the periods, the building appears resistant to new climatic conditions of TMY. In each scenario, α always results equal or lower than 0.6. Although, it should be remembered that these values are obtained by averaging conditions of the whole year and the whole building, implying possible lower resilience during the hottest months and inside the most exposed zones of the facility. For these reasons, it is important to verify comfort conditions inside the building, that could not be present despite its climate resistance assessment. In addition, resistance is reduced moving through the years. This result is extremely important for understanding the possible difficulties that the built environment would face in the future.

5.1.1.3. Discomfort hours

A fundamental element of this work is the evaluation of safe and comfortable conditions inside the building, in presence of conventional and disrupting conditions. It is essential for the assessment of climate resilience of the system and final focus of this study.

In case of buildings without mechanical conditioning systems, the annual degree weighted discomfort hours can be evaluated. The amount of degree hours characterized by hot and cold discomfort along the occupied period are presented in Figure 22:

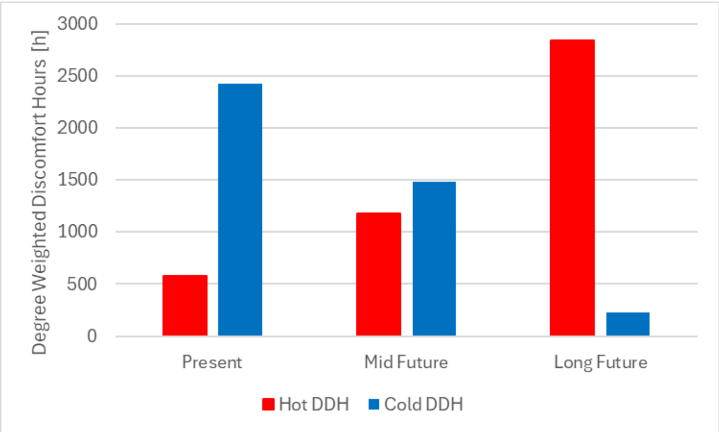


Figure 22: Hot and Cold Degree weighted discomfort hours during occupied hours of TMY in Base Case

The three time periods have different characteristics in terms of discomfort hours. In the Present scenario, cold discomfort hours, around 2500 h, are almost five times bigger than the hot ones, that are near 500 h. This confirms the necessity of using heating systems during winter and mild periods. In the Mid Future, discomfort hours are close to each other, being in the range between 1000 h and 1500 h. During Long Future, situation is opposite to the Present one. Hot discomfort hours are much higher than the cold ones, being the first close to 3000 h and the second around 250 h. This highlights the significant modification of conditions inside the building and the consequent necessity of an appropriated equipment for avoiding it.

5.1.1.4. Thermal survivability

Thermal survivability, evaluated from the values of HI, presents different levels during the year and the scenarios, as shown in Figure 23:

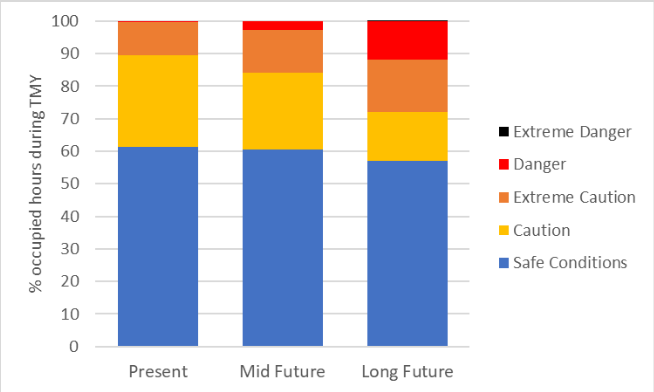


Figure 23: Survivability levels during TMY in Base Case

In all the periods, safe conditions are present for most of the time. In Present and Mid Future, the rest of the time is almost covered by caution and extreme caution conditions, except for 3% of hours with dangerous conditions in the second one. The third scenario, indeed, has different characteristics, as safe conditions are present for 57% of the time, caution and extreme caution conditions constitute 30% of it and the remaining 12% is covered by dangerous levels of HI. This last case is also characterized by the not evident, but significant, presence for the 0.1% of the time of extreme dangerous conditions.

From this last analysis, it emerges that the building is not adequate for the maintenance of safe and comfortable conditions in every occupied hour of the year, especially in future scenarios. It means that, even if it could react well to extreme weather, it would not necessarily be considered resistant to climate change scenarios. In addition, all the parameters that have been calculated above are able to assess only thermal resistance, safety and comfort related to hot exceedances. So, it is suggestable to also evaluate cold discomfort during the year.

5.1.1.5. Analysis of the different thermal zones

After these considerations made at whole-building level, it is important to analyze singularly each thermal zone, to understand the differences between them in terms of internal conditions and which loads and aspects are more influential. This aspect has been highlighted in some previous studies, for example the ones of Ji et al. (145) and Hamdy et al. (146). In this way, it is possible to select which zones are more significant for the analysis, using them in some calculations. Investigated apartments are shown in the figure below. It is reminded that the south-exposed façade is indicated as "principal" and the north-exposed as "retro" one.

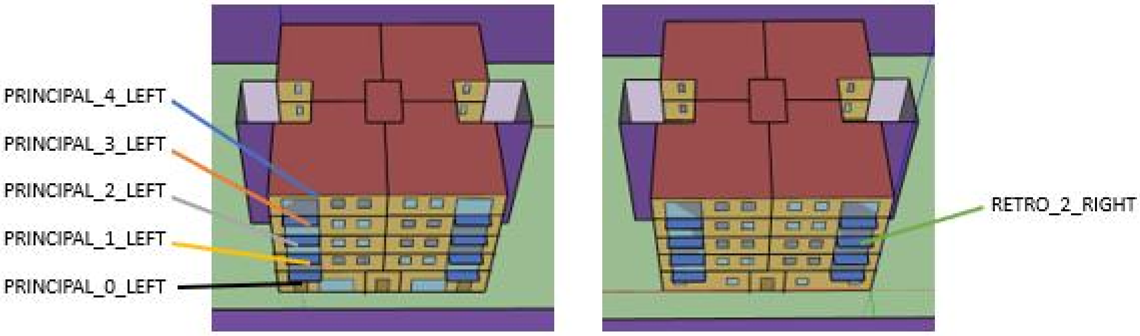
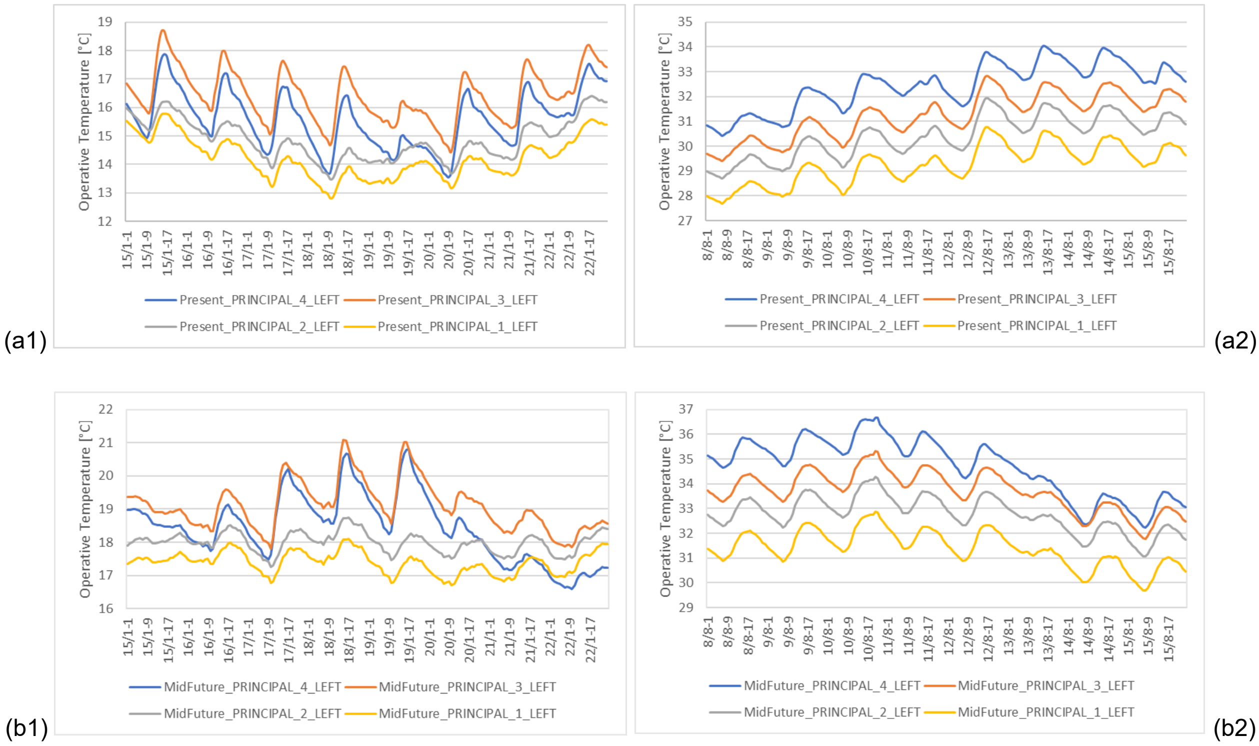
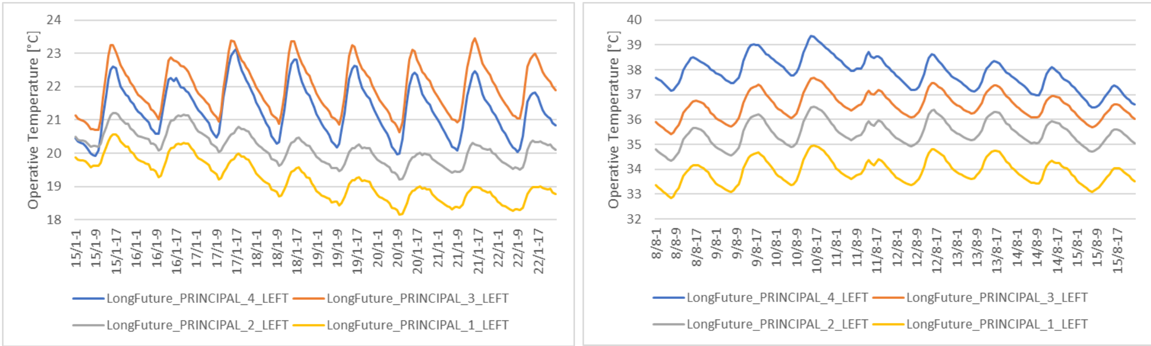


Figure 24: Investigated apartments of the south-exposed (PRINCIPAL) and north-exposed (RETRO) facades

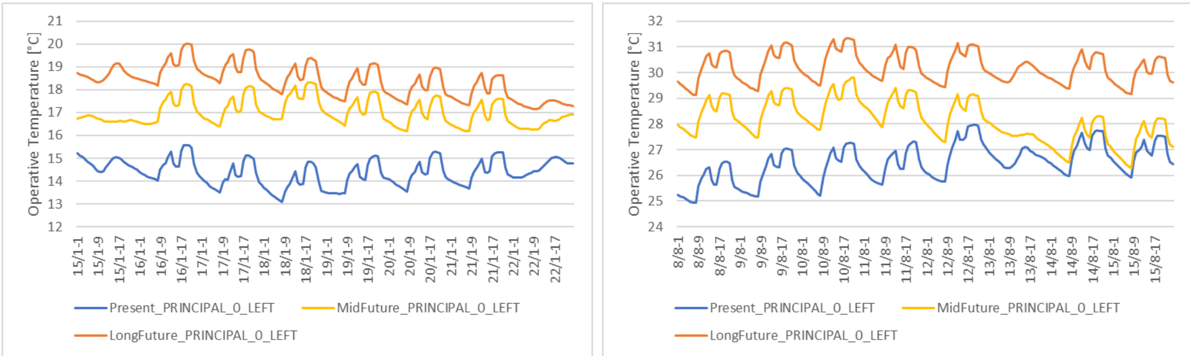
The first element investigated is the difference of operative temperature registered inside apartments with the same orientation but located in different floors. Trends are proposed for a winter and a summer period, where outside temperatures are the coldest and the hottest of the TMY. The different temperatures inside the apartments with same the expositions are shown in Figure 25. In Figure 26, evolution of temperatures inside the Shops for different time periods is presented.





(c1) (c2)

Figure 25: Operative Temperature inside Apartments in Base Case during winter period (1) and summer period (2), in Present (a), Mid Future (b) and Long Future (c) scenarios



(a) (b)

Figure 26: Operative Temperature inside Shops in Base Case during winter period (a) and summer period (b)

It is noticeable how location inside the building influences zone temperatures. This is mostly caused by exposure to outside air, wind and solar radiation. The 4th floor apartment is the most exposed to these elements in the whole building. This aspect causes the presence of low temperatures during winter and high ones during summer. In fact, temperatures of the 3rd floor apartment result higher than the ones inside the 4th floor apartment during winter and the opposite during summer. Solar radiation plays an important role on the interior conditions, as it is noticed by lower temperatures, both during winter and summer, inside the bottom apartments. Along the scenarios, temperature difference between the floors is approximately constant, depending on outside temperature, internal loads and solar radiation. It is important to highlight how higher outside temperatures influence internal conditions, causing differences of almost 2 °C in the temperatures inside the same apartment, between each scenario. This aspect is noticeable in Figure 25 and Figure 26. Comparing the different zones, it is clear that Shops and 4th floor south-exposed apartments are the most critical ones for cold and hot discomfort, respectively. For this reason, one of them is selected for the analysis of temperature profiles, object of sections 935.3.4 and 5.4.4.

Evolution of operative temperature in the most exposed apartment along the years is presented in Figure 27.

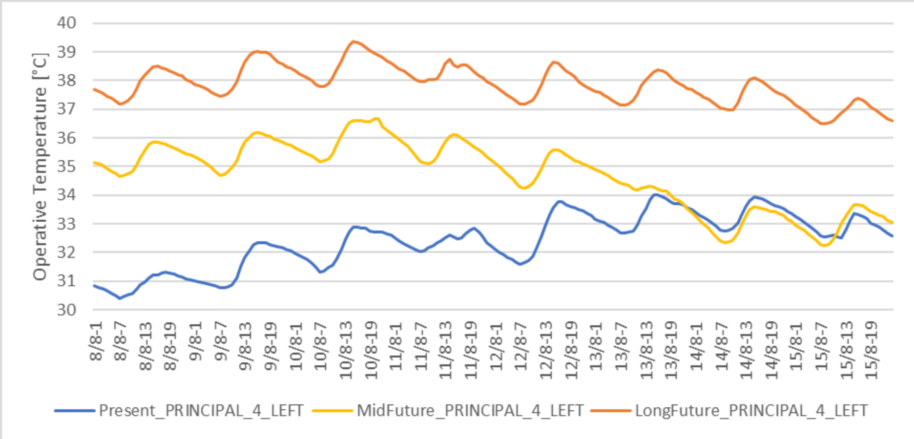


Figure 27: Operative Temperature inside the most exposed apartment in Base Case during hottest period of the year

During the hottest period of the year, temperatures reach considerable high values. Maximum values are 34.0 °C, 36.7 °C and 39.4 °C for Present, Mid Future and Long Future. These numbers are results of inadequate envelope and ventilation parameters for resisting to outside ambient conditions, especially during the summer period. In fact, extremely warm conditions outside and low ventilation rates maintained for long periods, combined with the constant presence of internal heat gains and solar radiation, unable inside temperatures to reduce until suitable values.

The considerable influence of solar radiation on internal temperature is shown in Figure 28.

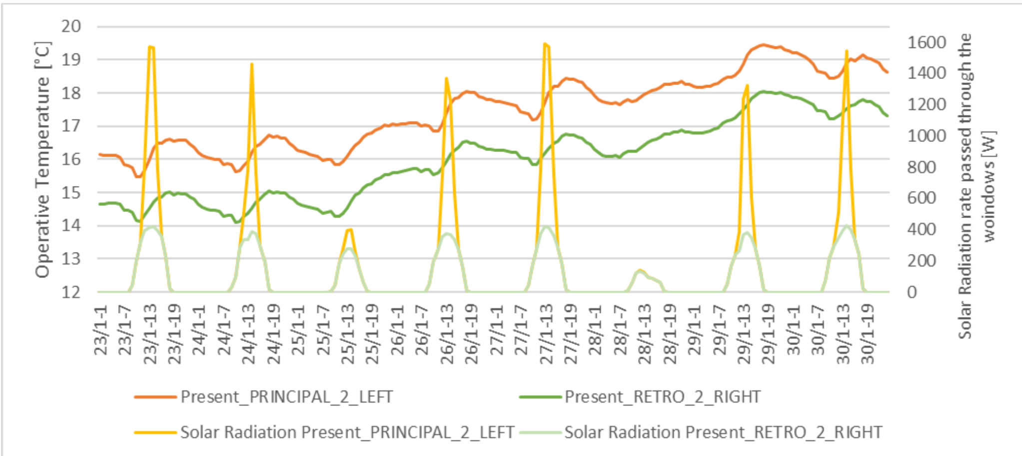


Figure 28: Operative Temperature and Solar Radiation for apartments with different expositions in Base Case in Present Scenario

In a week of January, the south-exposed apartment presents temperatures almost 1.2 °C higher than the corresponding north-exposed. Solar radiation that passes through the glazing, and consequently the one that arrives on the façade of the building, is significantly higher for the first apartment. In addition, it is evident that on the 28th of January, when solar radiation is lower, temperature peak in the afternoon significantly lower than the ones of the other days.

Effect of internal heat gains on interior temperature can be visualized in Figure 26, where temperatures present lower values during midday, when there is no occupancy and electrical devices are turned off. In addition, on Sunday, when the shops are closed, temperatures present a lower incrementation and their profiles are driven only by exterior temperature and solar radiation.

5.1.2. HWs

After the description of the building's behavior to new typical weather conditions, it is important to analyze its reaction to extreme scenarios, such as heatwaves. As it is explained in the IPCC report of Working Group I of AR6 (20), these events will be more frequent and severe in the future, so the building should be prepared for them, maintaining safe and comfortable conditions inside as much as possible.

5.1.2.1. Energy needs

The first indicator for assessing the impact of these extreme periods on the system is the energy needs. Since they have different durations and characteristics, it is necessary to evaluate it also in terms of average daily request. From Table 19 it is possible to visualize total and daily energy needs during heatwave periods.

PRESENT HWs	Total Cooling Need [kWh/m^2_{cond}]	Daily Cooling Need [kWh/m^2_{cond}·day]
Longest	4.25	0.33
Most Intense	3.06	0.34
Most Severe	2.83	0.40

MID FUTURE HWs	Total Cooling Need [kWh/m^2_{cond}]	Daily Cooling Need [kWh/m^2_{cond}·day]
Longest	5.13	0.43
Most Intense	4.45	0.49

LONG FUTURE HWs	Total Cooling Need [kWh/m^2_{cond}]	Daily Cooling Need [kWh/m^2_{cond}·day]
Longest & Most Severe	20.99	0.58

Most Intense	3.75	0.54

Table 19: Energy needs during Heat Waves in Base Case

According to the previous results of TMY, needs increases along the scenarios, with a Long Future request consistently higher than the one of the Present. Most severe heatwaves are the ones that require more cooling energy in all the years, because of the presence of high daytime and nighttime temperatures during the whole period.

5.1.2.2. Climate resistance assessment

After these preliminary considerations regarding impact of heatwaves on the building and on the grid, it is possible to assess resistance of the building to these events. Calculated indicators are shown in Table 20.

PRESENT HWs	IOD	AWD	α
Longest	6.54	9.02	**0.72**
Most Intense	6.14	9.31	**0.66**
Most Severe	7.14	10.48	**0.68**
MID FUTURE HWs	IOD	AWD	α
Longest	7.48	10.44	**0.72**
Most Intense & Severe	8.10	11.37	**0.71**
LONG FUTURE HWs	IOD	AWD	α
Longest & Most Severe	10.08	13.49	**0.75**
Most Intense	9.54	14.28	**0.67**

Table 20: Resilience Indicators during HWs in Base Case

In these scenarios, AWDs present values much higher than the ones calculated for the TMYs, shown in Table 18. However, it should be reminded that for the whole year, AWD values are low also because all the occupied hours of the year are considered, even if outside temperatures are lower than the reference one. Considering the same typology of heatwave, differences in AWD between heatwaves of Present and Mid Future is around 1.5 °C, whereas the ones between Mid Future and Long Future is around 3.0 °C. These data confirm, also in case of heatwaves, the strong differences between present and future weather data.

Considering the effect of extreme weather, IODs provide a global description of its impact. Also in this case, values are significantly worse than the ones of TMY. In fact, during Present, Mid Future and Long Future, average operative temperatures during the occupied hours are up to 6.1 °C, 7.5 °C and 9.5 °C higher than the comfort temperature limit of 26 °C. In particular, the most severe heatwaves are the ones with the biggest impact on the interior environment. This result is explained by the high AWD values. Most Intense heatwaves are the ones with a lower, but still consistent, effect on the inside temperatures. This is because of both their global lower temperatures, compared to the most severe, and duration, respect to the longest. This affirmation is not true when the most intense heatwaves coincide with the most extreme of other categories, like it happens in the Mid Future scenario, where one heatwave corresponds not only to the most intense, but also to the most severe of the period.

Finally, α assesses resistance of the building to these extreme weather events. As it is seen from Table 20, values for this parameter are always lower than 1. This confirms the ability of the building to resist extreme weather conditions. Although, it should be noted that results are worse compared to the ones achieved during TMY, shown in Table 18. This highlights the stress caused by extremely warm periods on buildings. Among the different types of heatwaves, the longest are the ones that obtain the worst results in terms of resilience, despite the lower AWD values. This points out the crucial role of duration for overheating risk. The same result was assessed by Sengupta et al. in their work (155). Respect to TMY, any significant difference between time periods is detected. This behavior assesses dependency of resilience not only on the magnitude of outdoor temperatures, but also on the duration and temperature trends of each heatwave.

5.1.2.3. Discomfort hours

Hot discomfort during occupied hours along heatwave periods is assessed with hot DDH. The calculated values are presented in Figure 29:

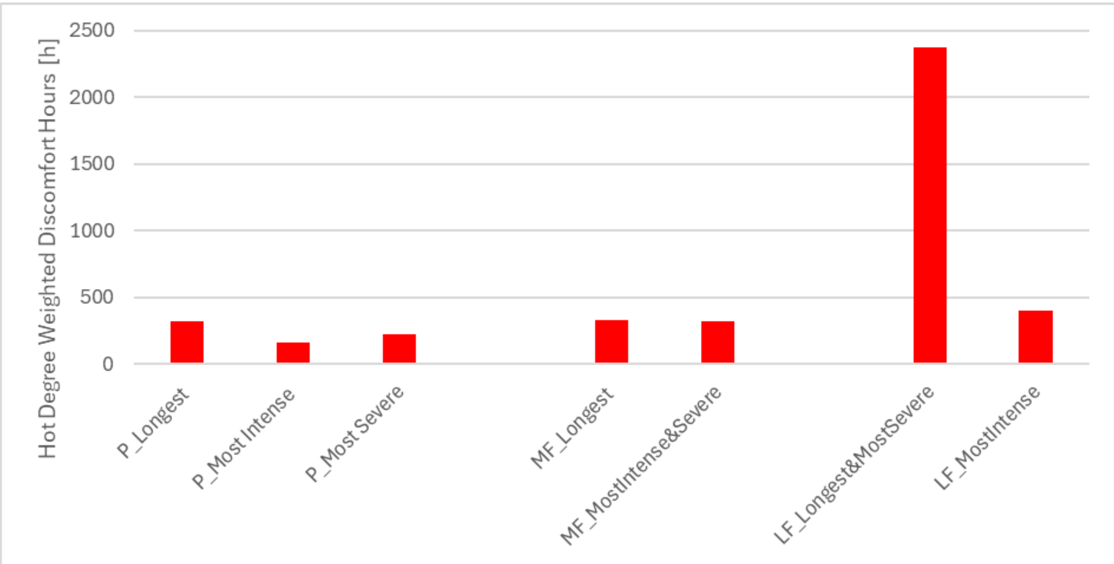


Figure 29: Hot degree weighted discomfort hours during occupied hours of HWs in Base Case

It is important to highlight that DDH cannot be compared for different periods. In any case, it is possible to say that, from a qualitative point of view, future heatwaves have a major influence on people’s discomfort. Also, considering the duration of HW periods respect to the one of TMYs, it is reasonable to affirm that these abnormal events have a more significant impact on comfort inside the building respect to the average weather conditions.

5.1.2.4. Thermal survivability

To validate the assessment of resilience of the building to extreme events, it is necessary to verify survivability inside it. From Figure 30it is possible to visualize the levels of survivability during heatwaves for all the scenarios.

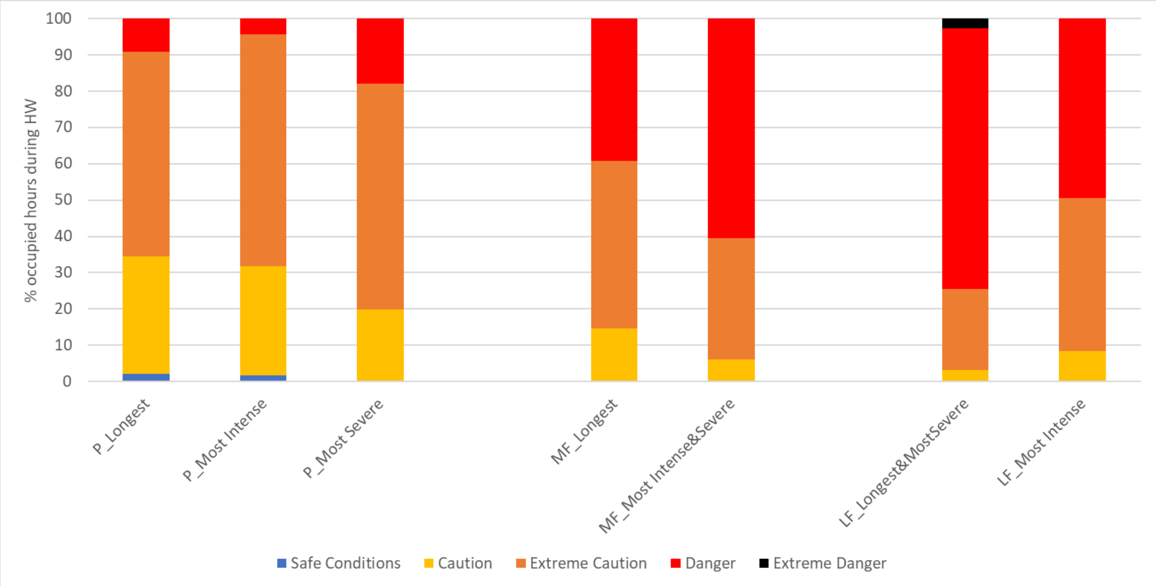


Figure 30: Survivability levels during occupied hours of HWs in Base Case

Results are different among each HW type and time period.

For the Present, Safe Conditions figure only for the Longest and Most Intense heatwaves, for a time corresponding, respectively, only at 2.1% and 1.7% of the occupied hours. For all the three types, most of the time is characterized by Extreme Caution conditions, that are equal to the 56.5%, 64.0% and 62.2% of Longest, Most Intense and Most Severe heatwaves. The rest of the time is covered by Caution conditions, respectively for 32.3%, 30.0% and 19.9% of the hours, and Danger conditions, for 9.1%, 4.3% and 18.0% of them.

In the Mid Future scenario, Safe Conditions are not present. Caution conditions have a low weight on the total hours, covering only 14.7% of the Longest HW and 6.2% of the Most Intense and Severe. Most of the hours of the Longest HW are characterized by Extreme Caution conditions, corresponding to 46.0% of the total, and the rest by Danger ones, which correspond to 39.2%. The other heatwave, indeed, is covered by Danger conditions for most of the time, for a total of 60.5% of the hours, and the rest by Extreme Caution ones, that are 33.3% of the total.

Like the previous case, in Long Future no Safe Conditions are present. In addition, most of the time is covered by Danger conditions, which are 71.8% of the Longest and Most Severe heatwave and 49.4% of the Most Intense. For the first scenario, Caution, Extreme Caution and Extreme Danger conditions constitute 3.2%, 22.2% and 2.8% of the occupied hours. In the second case, Caution and Extreme Caution conditions represent 8.3% and 42.3% of the time.

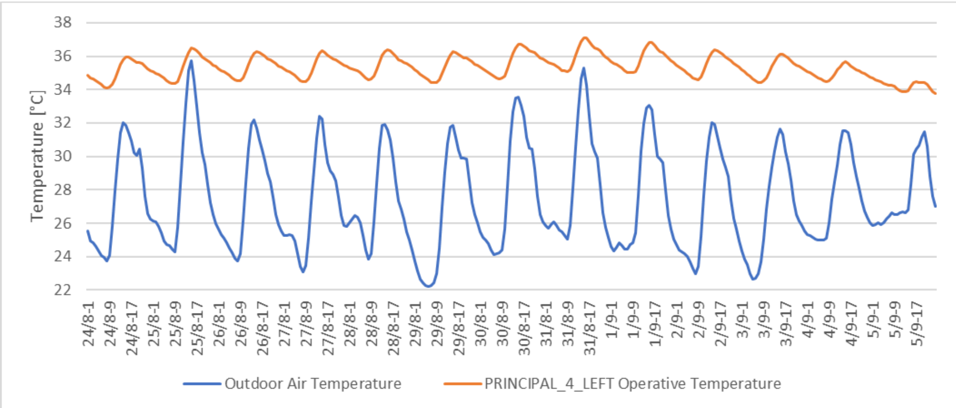
It is important to highlight the more severe impact of heatwaves on the indoor conditions with the increase of the years. Starting from the Present, where Dangerous conditions are present for a minor part of the hours, they arrive to constitute the biggest part of them for the Long Future scenario. In this last case, also, Extreme Dangerous conditions are present for the Longest and Most Severe HW.

For all the three time periods, Most Severe heatwaves are the most critical for the building. They present a number of hours characterized by Danger conditions always higher than the other heatwaves of the same time period. Another interesting consideration is regarding Longest heatwaves, since they are responsible for the creation of dangerous or caution conditions not only for their temperatures, but mostly for their duration. In addition, if their length is combined with high temperature values, like in one of the Long Future scenarios, extremely dangerous conditions are generated inside the building.

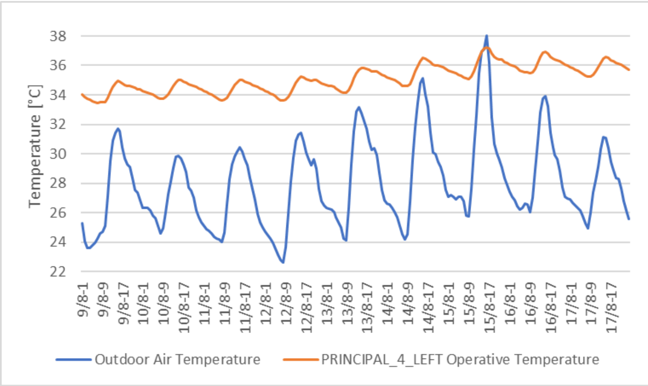
From the survivability and comfort analysis during heatwave events, results obtained showed that the building is not adequate to resist these extreme events, neither in the present year nor in the future ones.

5.1.2.5. Analysis of temperature inside the critical thermal zones

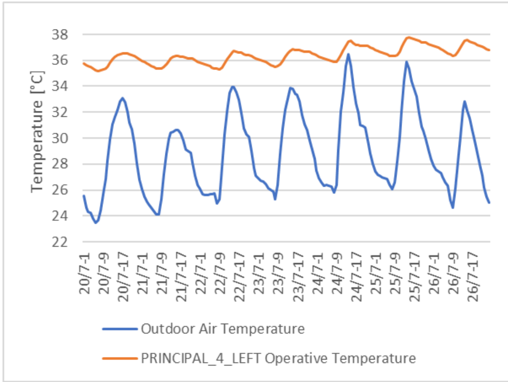
From Figure 31, Figure 32 and Figure 33, it is possible to see how the most exposed apartment reacts to extreme weather.



(a)

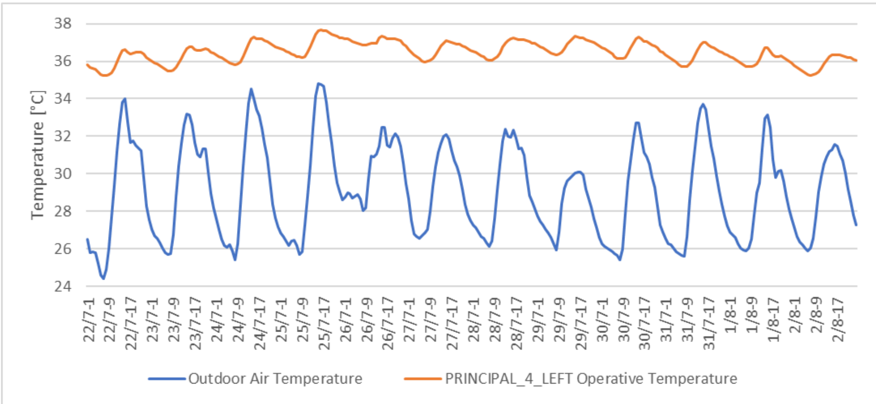


(b)

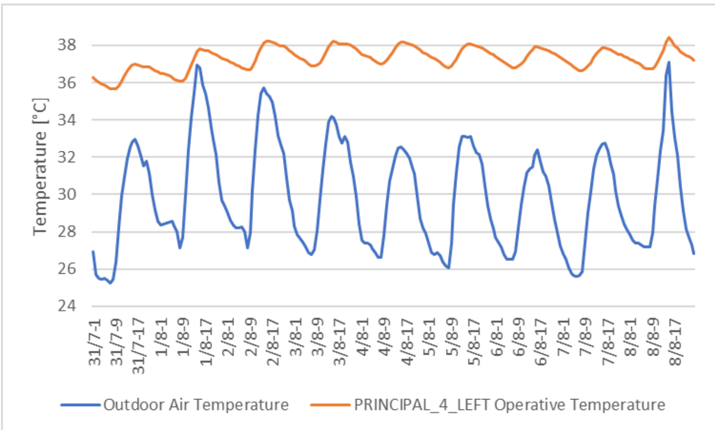


(c)

Figure 31: Operative Temperature inside the most exposed apartment in Base Case during (a) Longest (b) Most Intense (c) Most Severe Present HW

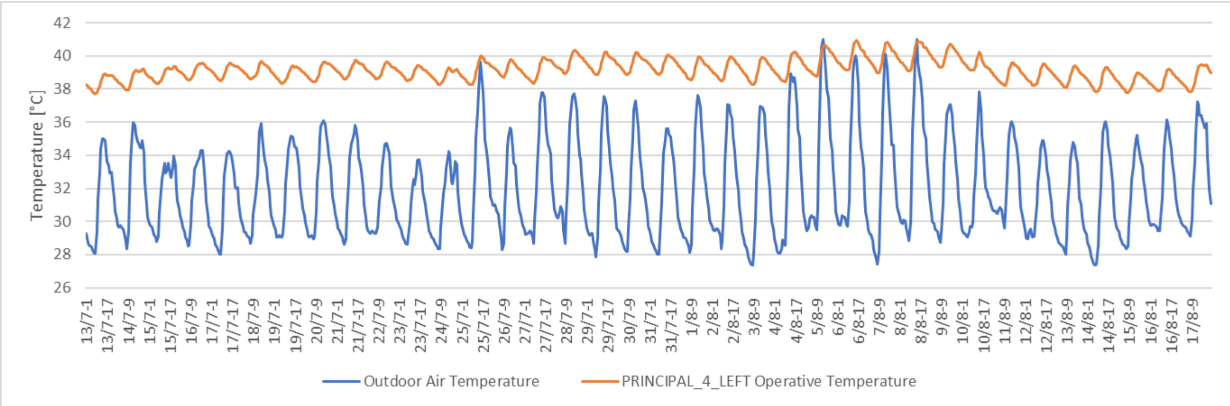


(a)

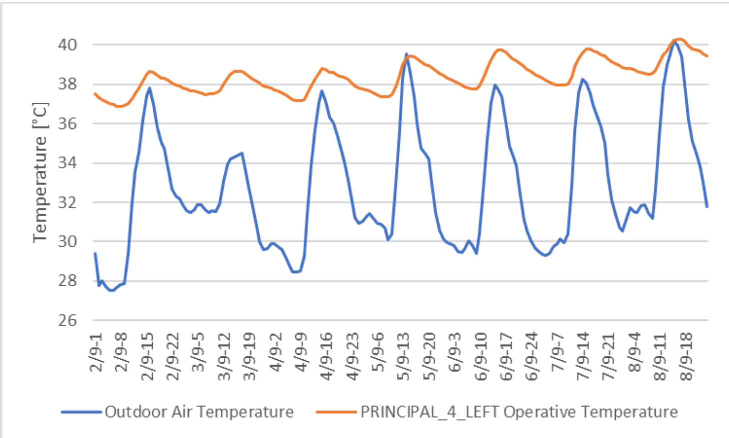


(b)

Figure 32: Operative Temperature inside the most exposed apartment in Base Case during (a) Longest (b) Most Intense and Severe Mid Future HW



(a)



(b)

Figure 33: Operative Temperature inside the most exposed apartment in Base Case during (a) Longest and Most Severe (b) Most Intense Long Future HW

Unfortunately, temperatures reach extremely high values in all the scenarios, even higher than outside temperature. This effect, as explained before, is caused by low ventilation rates, presence of internal heat gains and incidence of solar radiation.

Average inside temperatures increase along the scenarios, attesting between 34 °C and 38 °C for the Present, between 35 °C and 38 °C for the Mid Future and between 37 °C and 41 °C for the Long Future. This growing trend is caused by higher average daily temperatures moving through the years. In all the periods of time, Most Severe heatwaves are the ones where higher temperatures are achieved, because of the maintenance of more critical conditions outside.

Indoor temperature is sensible to outside temperature variation, especially during nighttime. This is caused by the thermal inertia of the envelope, which accumulates thermal and solar radiation during the day and re-emit it at night. When nighttime temperatures are high and similar to the ones of daytime, operative temperatures inside are not able to decrease easily, since envelope cannot dissipate well the energy accumulated during the day to outside and heat flux from indoor to outdoor space is penalized because of low temperature gradients. This phenomenon is visible in the Longest HW of the Mid Future scenario, in Figure 32, where temperatures around the 90th hour, that is supposed to be nighttime, have values much higher than in the nights of the other days. For this reason, maximum operative temperature excursion, that is usually slightly higher than 1 °C during the day, is clearly less than 1 °C, around 0.7 °C. So, it is evident how nighttime outside temperature influences daily decrease of inside temperature. On the other hand, maximum daily outside temperature influences the maximum operative one reached inside the apartment. In the days with these high picks, internal temperatures increase faster than the other days, getting extremely high values. This effect can constitute a serious problem in case of severe heatwaves, where temperatures are kept high for the whole day, even if heatwave duration is not very long.

From this starting analysis during TMY and HWs, it is evident that the building should be modified to be resistant to present and future weather and to achieve minimum comfortable and safe conditions inside it, especially during extreme events. Solutions can manage to increase air renovation when it is possible, reduce solar heat gains, insulate the most critical components of the building envelope, like roof and windows and implement some active cooling techniques.

5.2. Performances of cooling technologies during TMY

Analyzing the building's behavior during typical and extreme climate conditions, in chapter 5.1, it was discovered that it is not able to resist them, achieving very uncomfortable and unsafe conditions inside it, especially in the summer period. Causes of these conditions are inadequate characteristics of the envelope, that have been designed in presence of different available technologies and weather conditions, low ventilation rates, corresponding to the minimum values that are imposed from actual normative, and the presence of internal heat gains, produced by people and electrical equipment, and incident solar radiation (194).

To reduce their effects and try to achieve comfortable conditions, different cooling technologies are implemented in the building. Both passive and active ones are studied, singularly, to test their impact on the system, and combined, whenever possible and useful. Category A technologies are tested at first in free running conditions and later combined with Category B cooling technologies. In the same way, performances of these last ones are evaluated without and with modifications on the envelope.

5.2.1. Climate resistance assessment

It is important to visualize how cooling techniques improve resistance of the building to new climatic conditions. Calculated values of IOD, AWD and α for the three periods are shown in the table below.

	Present 2005-26			Mid Future 2041-60			Long Future 2041-60		
	IOD	AWD	**α**	IOD	AWD	**α**	IOD	AWD	**α**
Base Case	1.14	2.21	**0.52**	1.57	2.80	**0.56**	2.41	4.06	**0.60**
GrRf	0.84	2.21	**0.38**	1.20	2.80	**0.43**	1.98	4.06	**0.49**
Bl	0.75	2.21	**0.34**	1.08	2.80	**0.39**	1.87	4.06	**0.46**
AdWind	0.89	2.21	**0.40**	1.25	2.80	**0.45**	2.05	4.06	**0.50**
GrRf+AdBl	0.35	2.21	**0.16**	0.62	2.80	**0.22**	1.34	4.06	**0.33**
GrRf+AdBl+AdWind	0.34	2.21	**0.16**	0.60	2.80	**0.21**	1.30	4.06	**0.32**
NV	0.38	2.21	**0.17**	0.66	2.80	**0.24**	1.41	4.06	**0.35**
GrRf+NV	0.25	2.21	**0.11**	0.50	2.80	**0.18**	1.20	4.06	**0.30**
AdBl+NV	0.24	2.21	**0.11**	0.48	2.80	**0.17**	1.16	4.06	**0.29**
AdWind+NV	0.25	2.21	**0.12**	0.50	2.80	**0.18**	1.10	4.06	**0.27**
GrRf+AdBl+NV	0.10	2.21	**0.04**	0.30	2.80	**0.11**	0.91	4.06	**0.22**
GrRf+AdBl+AdWind+NV	0.08	2.21	**0.03**	0.26	2.80	**0.09**	0.85	4.06	**0.21**
AC	0.30	2.21	**0.13**	0.38	2.80	**0.14**	0.53	4.06	**0.13**
GrRf+AC	0.20	2.21	**0.09**	0.27	2.80	**0.10**	0.41	4.06	**0.10**
AdBl+AC	0.19	2.21	**0.09**	0.26	2.80	**0.09**	0.41	4.06	**0.10**
AdWind+AC	0.22	2.21	**0.10**	0.29	2.80	**0.10**	0.42	4.06	**0.10**
GrRf+AdBl+AC	0.07	2.21	**0.03**	0.13	2.80	**0.05**	0.28	4.06	**0.07**
GrRf+AdBl+AdWind+AC	0.07	2.21	**0.03**	0.12	2.80	**0.04**	0.25	4.06	**0.06**

Table 21: Climate resistance indicators during Present, Mid Future and Long Future TMY for the cooling technologies implemented

Looking at the results of the single Category A techniques, they contribute to the reduction of IOD, respect to the Base Case, of approximately 0.30 °C for the Present scenario, 0.35 °C for the Mid Future and 0.40 °C for the Long Future. Along the scenarios, advanced solar shading is the single technology that allows a lower increase of indoor temperatures. The combination of two or three technologies considerably improves the IOD, reducing overheating of approximately 0.80 °C during Present, 0.96 °C in Mid Future and 1.09 °C in Long Future.

Natural ventilative cooling is extremely effective in the closer years, but it loses its power for the further ones. This behavior was also evaluated by Borghero et al. in the apartment of Badalona (150). Combining it with one passive technology, it is possible to reduce temperature exceedance of 0.90 °C in the Present scenario, 1.09 °C in the Mid Future one and of 1.31 °C in the Long Future. In case of combination of it with more technologies, temperatures decrease by an additional value, in the range of 0.15 °C and 0.25 °C, depending on the techniques and on the scenario.

Vapor compression refrigeration maintains low IODs in all the scenarios. When it is implemented alone, values obtained, for Present, Mid Future and Long future scenarios, are equal to 0.30 °C, 0.38 °C and 0.53 °C. Also this technology obtains different performances along the time periods, but less significant than the ones obtained for passive ones, that are more sensible to outdoor conditions. Integrating passive measures in a building with AC, operative temperature decreases, reducing the parameter of almost 0.23 °C, 0.26 °C and 0.28 °C with respectively one, two or three measures implemented. Effectiveness is approximately the same in each scenario, increasing slightly along them. It is important to highlight that values of IOD in presence of Vapor compression refrigeration are different from zero because of a different set point value of air temperature during night, of 28 °C instead of 26 °C, and because of the values of mean radiative temperature inside the apartments, that increase the operative one. It is evident that, even if the sizing is made considering climate changes along the years, disrupting events can affect the efficiency of this type of technology. Average values of overheating degree in the future scenarios are slightly higher than the ones in the present, because of the increment on the severity of temperatures along the years, that unable the obtainment of comfort conditions without modification of cooling setpoint temperature.

In terms of escalation factor α, it is noticeable how each technology helps in the reduction of the index. It is evident how their effectiveness decreases along the years, because of the worse outdoor conditions. Among the single Category A measures, advanced solar shading is the one that guarantees the best results, slightly better than the others. Natural ventilative cooling can significantly help the building against close climate changes, mostly thanks to low temperatures during night and maximum temperatures not so extreme. As was explained before, increasing temperatures disturb applicability and effectiveness of this technology, which, in any case, guarantees building resistance to weather change. Its combination with other passive measures, allows to reach excellent results for the Present and Mid Future scenarios and others satisfactory for the Long Future, where the worst value for α is 0.30, in case of green roof. According to this indicator, use of vapor compression refrigeration ensures the building's resistance to present and future weather. Values obtained are around 0.13 in case of single application of this technique, whereas they decrease until 0.03 with other passive measures applied.

With this analysis, the importance of adequate ventilation rates, that, in case of natural ventilative cooling, are significantly higher than the ones of the Base Case, was highlighted. The same aspect was pointed out by Hamdy et al. for Dutch dwellings (146). Category B technologies confirmed themself as the most effective for reducing internal overheating, but it should be reminded that natural ventilative cooling is badly affected by the increasing of outside temperatures. In both cases, with and without natural ventilative cooling implemented, the use of at least two Category A technologies is recommended for all the scenarios, for achieving an adequate resistance to TMY climate changes.

5.2.2. Discomfort hours

Starting from the climate resistance analysis, it is possible to visualize how the different cooling measures impact on comfort inside the building. Discomfort hours inside dwellings without mechanical conditioning systems are shown in Figure 34.

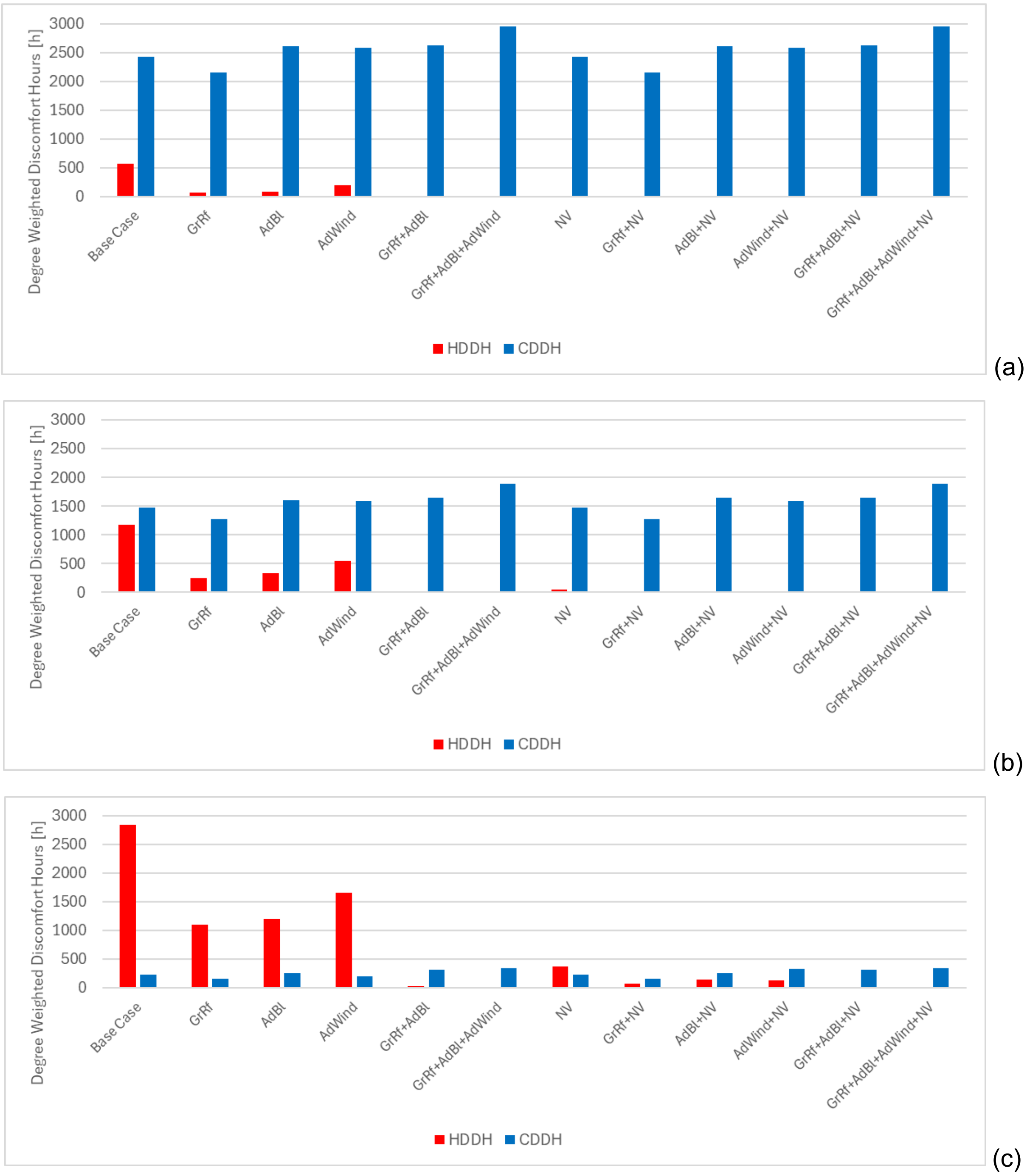


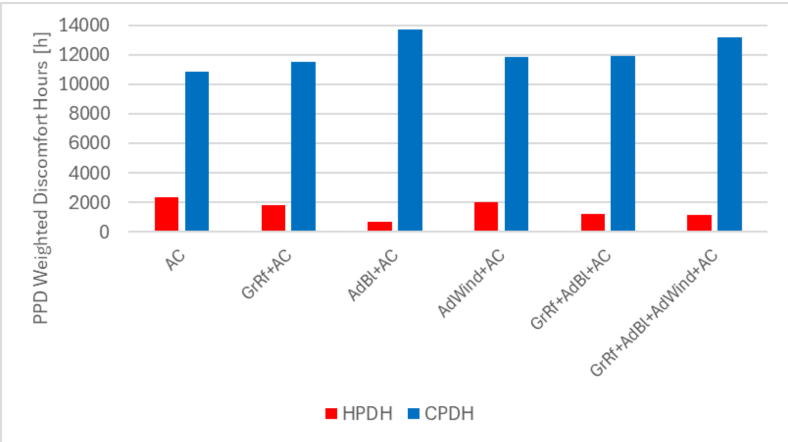
Figure 34:Annual Hot and Cold Degree weighted discomfort hours during (a) Present (b) Mid Future (c) Long Future TMY for the different passive cooling technologies implemented

It is evident that all cooling technologies have a positive impact on hot discomfort, but their presence during winter or intermediate seasons can increase the cold one.

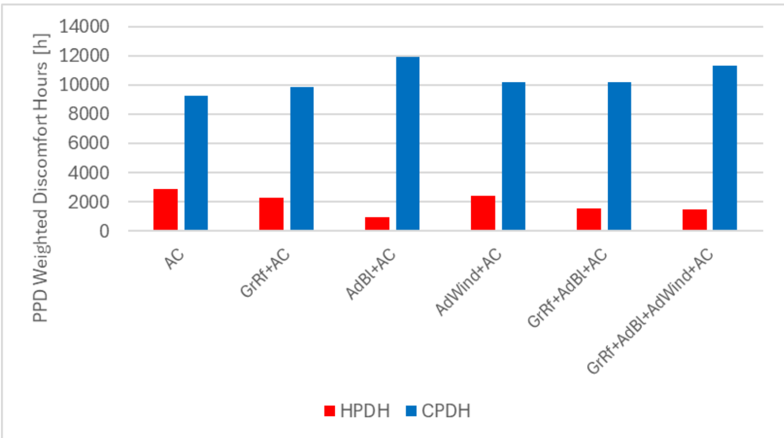
In each of the three scenarios, single Category A measure cannot turn to zero the HDDH. On the other hand, combining them together or with natural ventilative cooling, this goal is easily reached during Present and Mid Future, but not in Long Future, where only combination of three passive techniques obtains it. As commented in the previous paragraph, natural ventilative cooling loses its effectiveness in the future scenarios, because of the higher average outdoor temperature.

Regarding cold discomfort, it is reduced by green roof, but it is slightly increased by advanced solar shading and advanced glazing. Basing on this, it is affirmable that technologies that reduce heat exchange between indoor and outdoor have a positive impact on both comfort conditions, while the ones that reduce solar gains can have a negative contribution on the cold one. Advanced glazing, which performs both reductions, behaves in a different way, depending on the scenario.

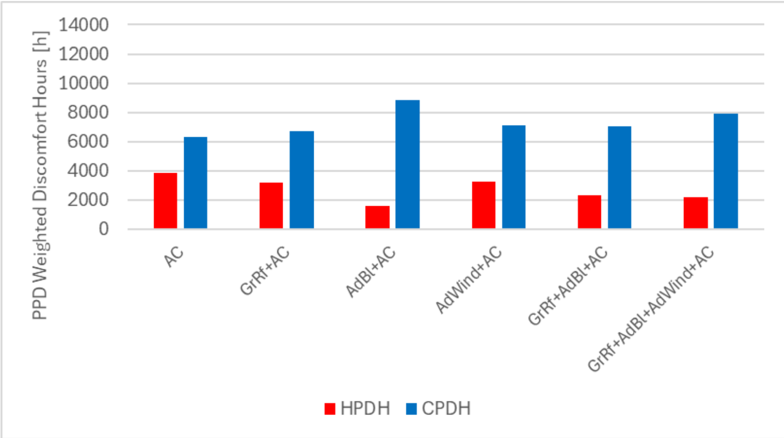
In buildings where active cooling systems are present, discomfort conditions are evaluated basing on PPD weighted discomfort hours. It is important to mark that is not possible to compare in a quantitative way results of DDH and PDH, being the two models and indicators significantly different. Values of Hot and Cold PPD weighted discomfort hours are represented in Figure 35.



(a)



(b)



(c)

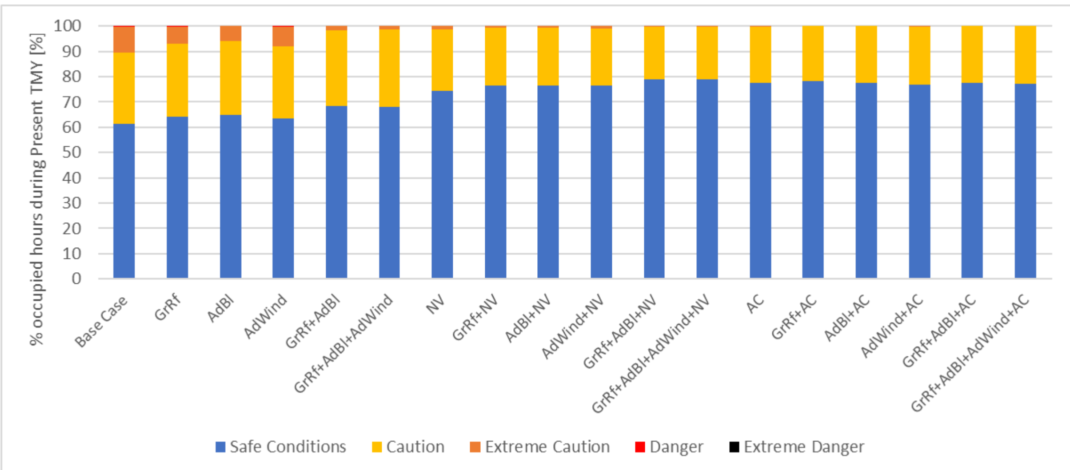
Figure 35: Annual Hot and Cold PPD weighted discomfort hours during (a) Present (b) Mid Future (c) Long Future TMY occupied hours for the different passive cooling technologies implemented with vapor compression refrigeration

The implementation of passive cooling technologies with vapor compression refrigeration ensures the obtainment of a lower number of occupied hours characterized by hot discomfort. Advanced solar shading with AC is the configuration that obtains the best results for hot discomfort in all the scenarios, even better than combinations of passive measures with AC. This is probably caused by the reduced solar gains and the lower thermal mass of the opaque and transparent components of the building's envelope.

On the other hand, the presence of cooling measures increases cold discomfort inside the apartments, reaching a significant number of CPDH. This should be seen in a critical way, considering that AC is not activated at all in winter and the presence of passive systems can enhance cold discomfort during the intermediate seasons.

5.2.3. Thermal survivability

Even if the effectiveness of cooling technologies on building resistance to future typical weather conditions was assessed, it is necessary to verify their contribution to comfort. Percentages of survivability levels, based on Heat Index, for the different techniques are presented below.



(a)

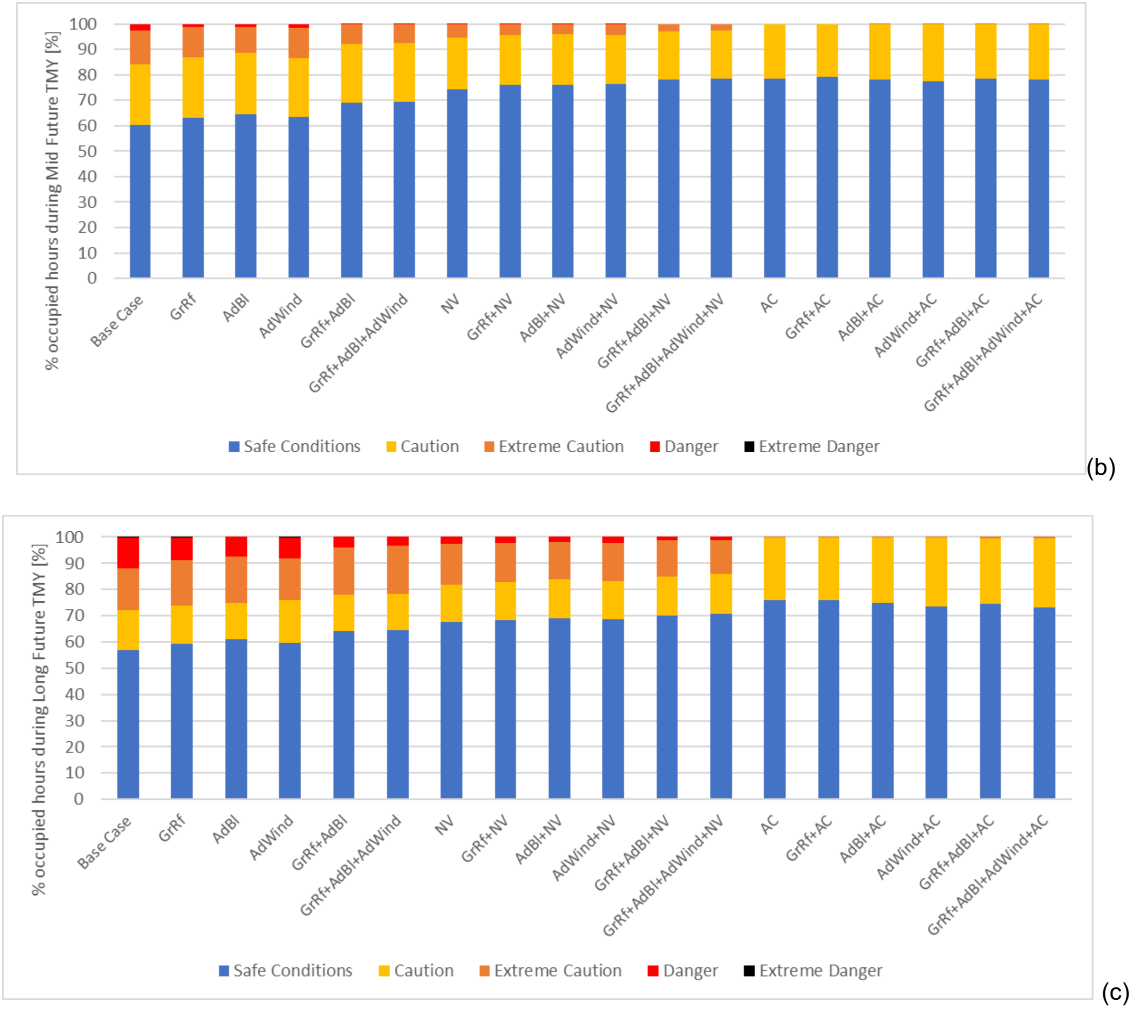


Figure 36: Survivability levels during (a) Present (b) Mid Future (c) Long Future TMY with cooling technologies implemented

Different results are obtained along the scenarios. As it is possible to see from Figure 366, for the Present, in case of free running conditions, only two or three Category A technologies are able to significantly reduce the percentage of extreme caution conditions up to 1.6% and 1.5%. Natural ventilative cooling, also alone, can increase Safe Conditions to 74.0% of occupied hours and reduce Extreme Caution ones until 1.3%. Adding one or more passive technologies, these results are improved.

During Mid Future, dangerous conditions are still present in case of one single Category A technology implemented. For this reason, at least two techniques are recommended to be installed. Also in this case, natural ventilative cooling with at least one Category A technology can increase safe conditions and also reduce the ones of caution. Adding other two or three passive cooling devices, dangerous conditions totally disappear.

Situation is worse along Long Future scenario, where dangerous temperatures are present in each configuration. In this case, natural ventilative cooling is effective only on safe, caution and extreme caution conditions, but not significantly on dangerous ones. For these last conditions, Category A technologies are more influential. So, the implementation of at least two of them is quite necessary to reduce the impact of more severe weather. In case of all the Category A technologies are installed, occupied hours are characterized by 70.5%, 15.3%, 13.1% and 1.1% of safe, caution, extreme caution and dangerous conditions.

Vapor compression refrigeration, indeed, can maintain satisfactory conditions in all the scenarios. Safe ones are maintained for the majority of the time, for at least 73.2% of the occupied hours. The remaining ones are covered only by caution conditions. In this case, passive technologies do not improve the performance of the system but, in contrast, they usually reduce them. In fact, increasing the number of passive technologies, safe conditions become less frequent. This behavior, opposite to the situations in absence and presence of natural ventilative cooling, can be explained by the presence of higher relative humidity values inside the building. This magnitude is dependent on indoor operative temperature, which, in case of many passive techniques installed, is lower because of lower mean radiant temperature of the building envelope. So, in case of equal absolute humidity level, higher percentages of relative humidity correspond to lower operative temperatures. This effect is evident in the cases with vapor compression refrigeration, since indoor air temperatures are the same for each combination of passive technologies and the differences in the Heat Index are related only to relative humidity levels.

5.3. Performances of cooling technologies during Heatwaves

After a starting study of the behavior of cooling technologies during the most probable meteorological year of present and mid-term and long-term future, that was useful for understanding their characteristics and impact on the energy needs, it is possible to move to the first disrupting event, the heatwaves.

The focus of this analysis is the maintenance of safe conditions inside the building, considering its resistance to the extreme events.

5.3.1. Climate resistance assessment

The first step is the resistance of the system to the unconventional climatic event. This aspect is determined by the quantification of indoor overheating, compared to severity of outside weather. Results are shown in the table below.

	Longest HW			Most Intense HW			Most Severe HW		
	IOD	AWD	**α**	IOD	AWD	**α**	IOD	AWD	**α**
Base Case	6.54	9.02	**0.72**	6.14	9.31	**0.66**	7.14	10.48	**0.68**
GrRf	5.59	9.02	**0.62**	5.12	9.31	**0.55**	5.95	10.48	**0.57**
AdBl	3.76	9.02	**0.42**	4.82	9.31	**0.52**	6.05	10.48	**0.58**
AdWind	5.33	9.02	**0.59**	5.14	9.31	**0.55**	6.32	10.48	**0.60**
GrRf+AdBl	3.48	9.02	**0.39**	3.38	9.31	**0.36**	4.32	10.48	**0.41**
GrRf+AdBl+AdWind	3.21	9.02	**0.36**	3.13	9.31	**0.34**	4.06	10.48	**0.39**
NV	3.76	9.02	**0.42**	3.78	9.31	**0.41**	4.77	10.48	**0.46**
GrRf+NV	3.14	9.02	**0.35**	3.10	9.31	**0.33**	4.02	10.48	**0.38**
AdBl+NV	2.74	9.02	**0.30**	2.94	9.31	**0.32**	4.04	10.48	**0.39**
AdWind+NV	2.92	9.02	**0.32**	3.00	9.31	**0.32**	4.03	10.48	**0.38**
GrRf+AdBl+NV	1.96	9.02	**0.22**	2.11	9.31	**0.23**	2.93	10.48	**0.28**
GrRf+AdBl+AdWind+NV	1.70	9.02	**0.19**	1.91	9.31	**0.20**	2.66	10.48	**0.25**
Air Conditioning	1.47	9.02	**0.16**	1.51	9.31	**0.16**	1.60	10.48	**0.15**
GrRf+AC	1.24	9.02	**0.14**	1.27	9.31	**0.14**	1.35	10.48	**0.13**
AdBl+AC	1.17	9.02	**0.13**	1.25	9.31	**0.13**	1.37	10.48	**0.13**
AdWind+AC	1.19	9.02	**0.13**	1.26	9.31	**0.14**	1.36	10.48	**0.13**
GrRf+AdBl+AC	0.85	9.02	**0.09**	0.94	9.31	**0.10**	1.07	10.48	**0.10**
GrRf+AdBl+AdWind+AC	0.76	9.02	**0.08**	0.88	9.31	**0.09**	0.97	10.48	**0.09**

(a)

	Longest HW			Most Intense & Severe HW		
	IOD	AWD	alpha	IOD	AWD	alpha
Base Case	7.48	10.44	**0.72**	8.10	11.37	**0.71**
GrRf	6.27	10.44	**0.60**	6.94	11.37	**0.61**
AdBl	6.38	10.44	**0.61**	6.82	11.37	**0.60**
AdWind	6.61	10.44	**0.63**	7.07	11.37	**0.62**
GrRf+AdBl	4.70	10.44	**0.45**	5.23	11.37	**0.46**
GrRf+AdBl+AdWind	4.47	10.44	**0.43**	4.95	11.37	**0.43**
NV	5.09	10.44	**0.49**	5.77	11.37	**0.51**
GrRf+NV	4.37	10.44	**0.42**	5.12	11.37	**0.45**
AdBl+NV	4.39	10.44	**0.42**	5.00	11.37	**0.44**
AdWind+NV	4.44	10.44	**0.43**	5.00	11.37	**0.44**
GrRf+AdBl+NV	3.44	10.44	**0.33**	4.07	11.37	**0.36**
GrRf+AdBl+AdWind+NV	3.21	10.44	**0.31**	3.81	11.37	**0.33**
Air Conditioning	1.64	10.44	**0.16**	1.69	11.37	**0.15**
GrRf+AC	1.38	10.44	**0.13**	1.46	11.37	**0.13**
AdBl+AC	1.43	10.44	**0.14**	1.46	11.37	**0.13**
AdWind+AC	1.41	10.44	**0.14**	1.46	11.37	**0.13**
GrRf+AdBl+AC	1.13	10.44	**0.11**	1.18	11.37	**0.10**
GrRf+AdBl+AdWind+AC	1.04	10.44	**0.10**	1.08	11.37	**0.10**

(b)

	Longest & Most Severe HW			Most Intense HW		
	IOD	AWD	alpha	IOD	AWD	alpha
Base Case	10.08	13.49	**0.75**	9.54	14.28	**0.67**
GrRf	8.68	13.49	**0.64**	8.67	14.28	**0.61**
AdBl	8.92	13.49	**0.66**	8.08	14.28	**0.57**
AdWind	9.13	13.49	**0.68**	8.31	14.28	**0.58**
GrRf+AdBl	7.13	13.49	**0.53**	6.97	14.28	**0.49**
GrRf+AdBl+AdWind	6.89	13.49	**0.51**	6.49	14.28	**0.45**
NV	7.72	13.49	**0.57**	7.69	14.28	**0.54**
GrRf+NV	6.92	13.49	**0.51**	7.13	14.28	**0.50**
AdBl+NV	6.99	13.49	**0.52**	6.69	14.28	**0.47**
AdWind+NV	7.00	13.49	**0.52**	6.78	14.28	**0.47**
GrRf+AdBl+NV	5.95	13.49	**0.44**	6.06	14.28	**0.42**
GrRf+AdBl+AdWind+NV	5.70	13.49	**0.42**	5.65	14.28	**0.40**
Air Conditioning	1.84	13.49	**0.14**	1.82	14.28	**0.13**
GrRf+AC	1.57	13.49	**0.12**	1.63	14.28	**0.11**
AdBl+AC	1.61	13.49	**0.12**	1.57	14.28	**0.11**
AdWind+AC	1.56	13.49	**0.12**	1.51	14.28	**0.11**
GrRf+AdBl+AC	1.31	13.49	**0.10**	1.35	14.28	**0.09**
GrRf+AdBl+AdWind+AC	1.19	13.49	**0.09**	1.21	14.28	**0.08**

(c)

Table 22: Climate resistance indicators during (a) Present (b) Mid Future (c) Long Future HWs with cooling technologies implemented

Considering implementation of only Category A technologies, it is evident how their effectiveness is reduced by higher severity of future heatwaves. In case of a single implemented measure, the resistance indicator always results higher than 0.34. This value is achieved and passed by multiple techniques installation in the Present scenario, but it is not the same in Mid and Long Future ones. Over the years, single passive techniques reduce indoor operative temperature respect to the Base Case of a value that is in the range between 0.87 °C and 2.78 °C, depending on the technology and the scenario. Appling two or three Category A measures, it is possible to decrease temperatures of almost another 2 °C and to achieve values of α between 0.34 and 0.53. Among the technologies, green roof is the technology that maintains similar performances in all the scenarios. On the other hand, effectiveness of advanced solar shading and advanced glazing resulted better than the ones of green roof for some HWs, but worse for others. In fact, their performances are strictly related to the magnitude of outdoor temperatures and duration of heatwave period, with

Natural ventilative cooling achieves very satisfactory resistance values in the Present, while its performances are reduced in Mid and Long Future. These results highlight the impact of heatwaves and climate change on the built environment, disabling the effectiveness of this kind of technology.

The technology that guarantees the best resistance in presence of heatwaves is vapor compression refrigeration. It allows an overheating degree of maximum 1.2 °C, during the worst scenario. In this way, also α maintains low values, all lower than 0.16. Its values decrease with the implementation of additional passive measures in the envelope. In contrast to what happens without and with natural ventilative cooling, there are not significant differences in case of installation of a single or multiple passive technologies and resilience is not affected by climate modifications, maintaining similar values along the years.

5.3.2. Discomfort hours

It is essential to validate the climate resistance assessment visualizing comfort conditions inside the apartments during these extreme events. Hot DDH and PDH, for all the configurations of cooling technologies, are presented in Figure 37, Figure 38 and Figure 39:

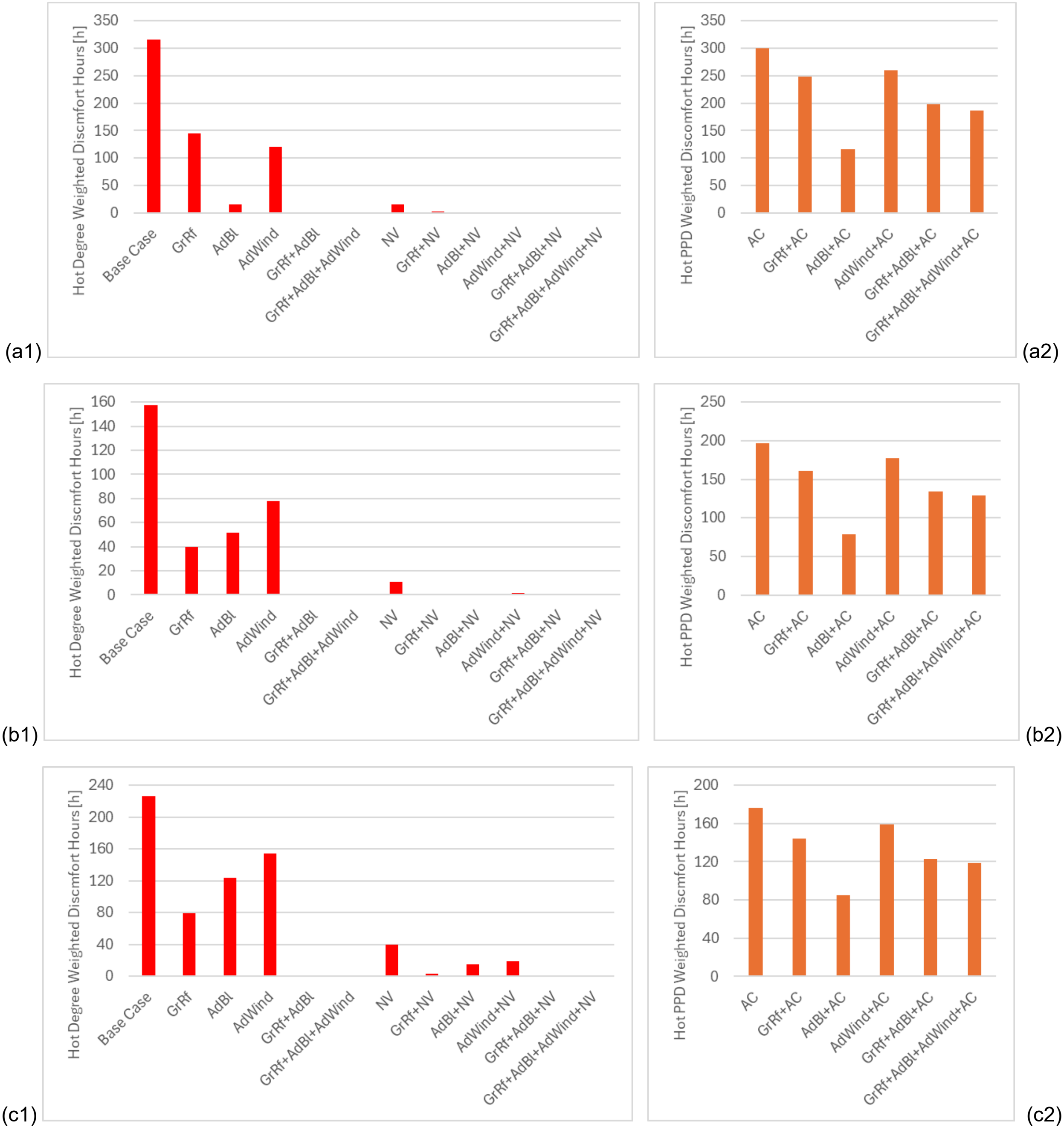


Figure 37: HDDH (1) and HPDH (2) during (a) Longest (b) Most Intense (c) Most Severe Present HW with cooling technologies installed

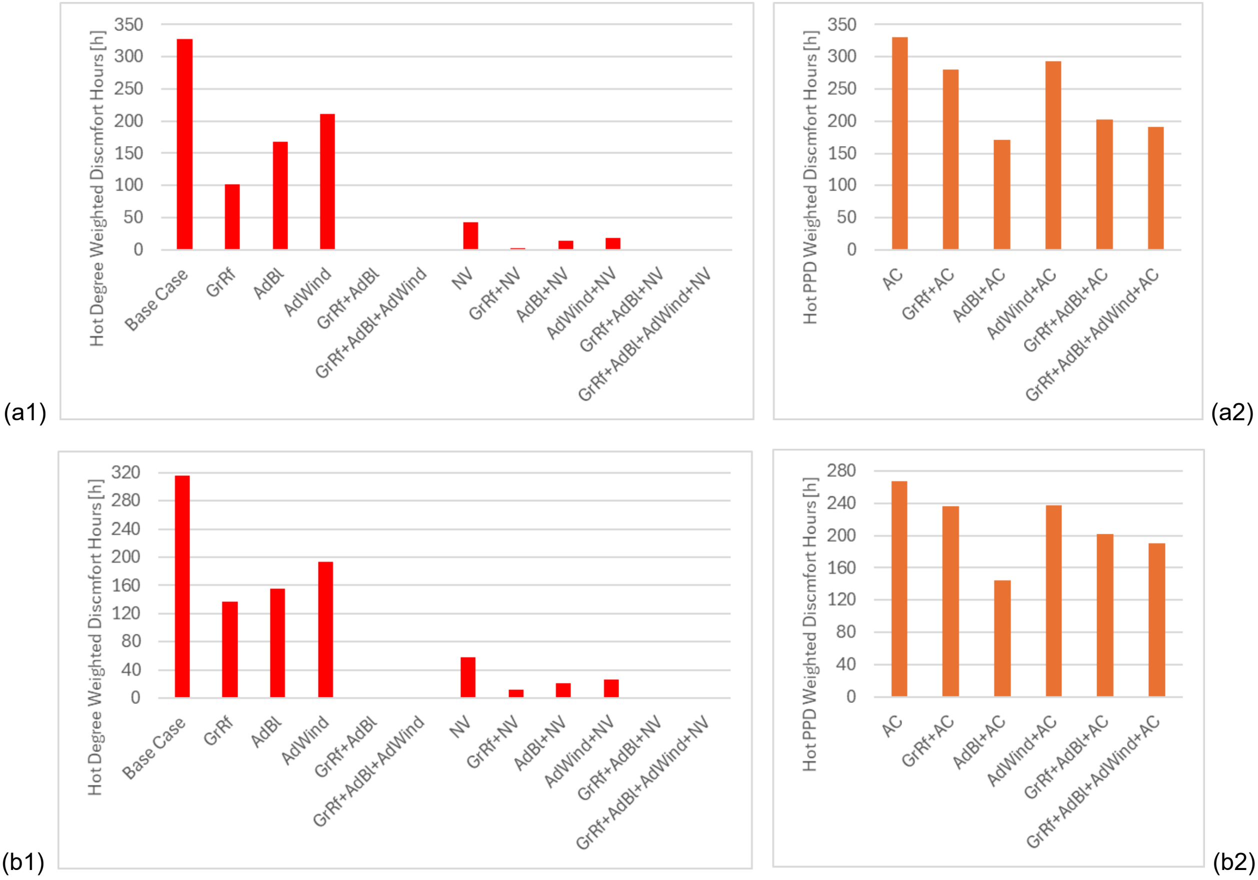
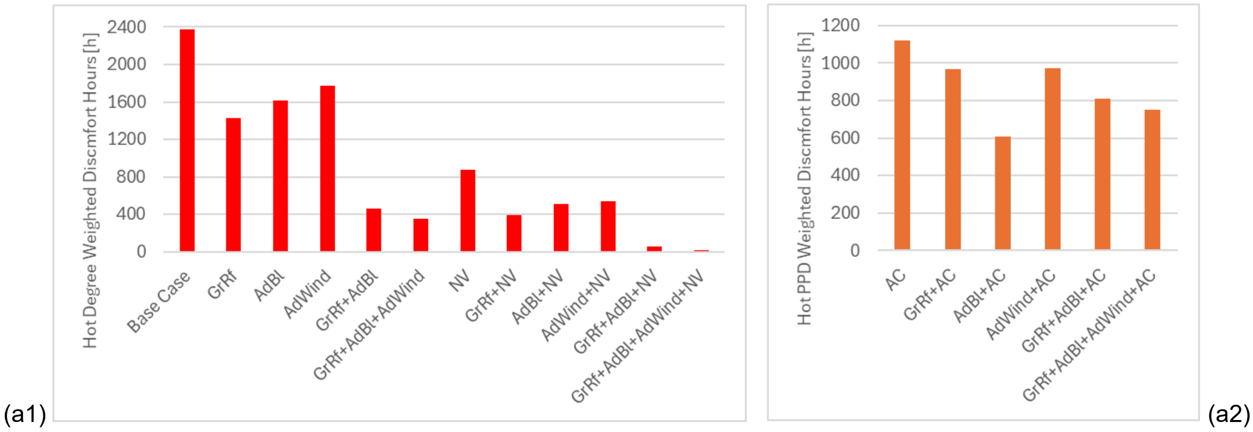
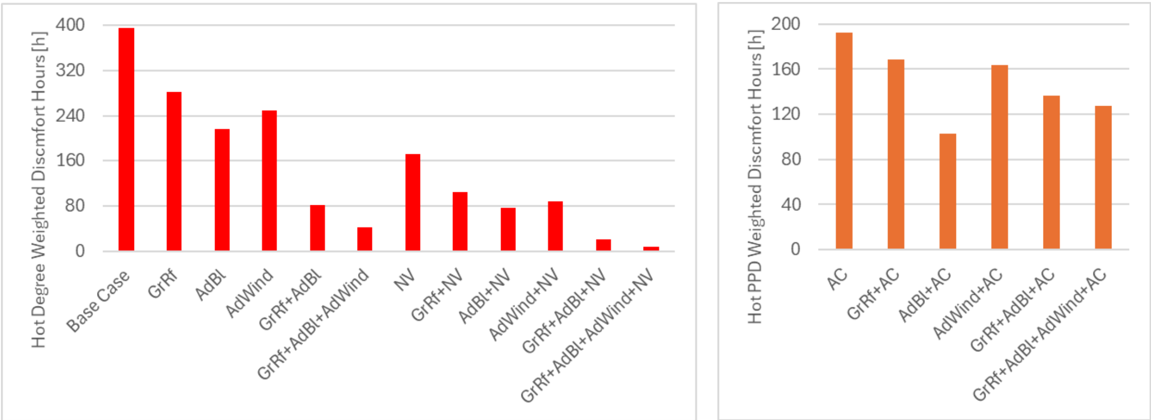


Figure 38: HDDH (1) and HPDH (2) during (a) Longest (b) Most Intense&Severe Mid Future HW with cooling technologies installed





(b1) (b2)

Figure 39: Figure 38: HDDH (1) and HPDH (2) during (a) Longest&MostSevere (b) Most Intense Long Future HW with cooling technologies installed

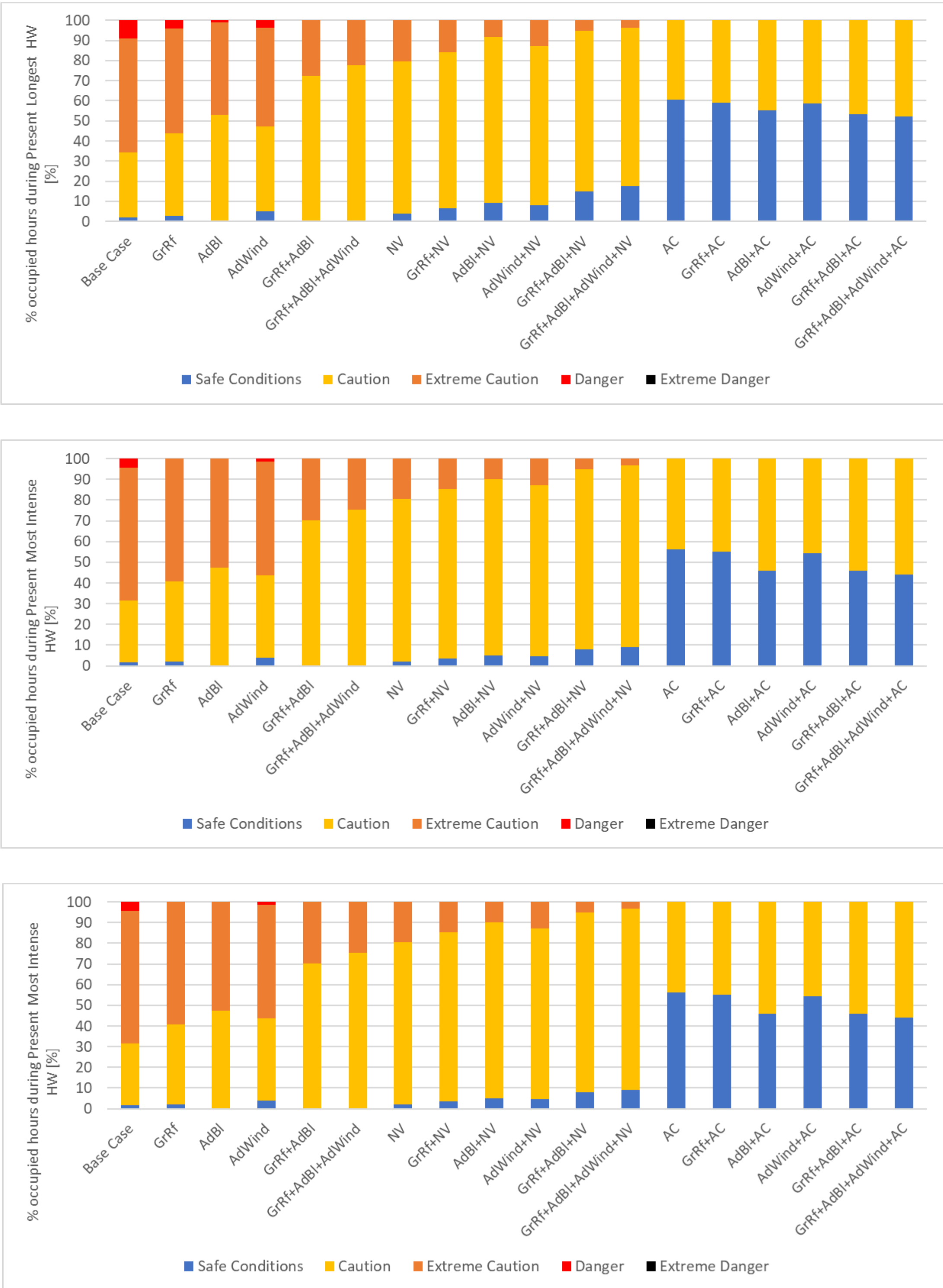
All the cooling techniques help in the reduction of hot discomfort inside the dwelling. Among the single Category A technologies in buildings without mechanical systems, green roof and advanced solar shading are the ones that performed better, the first achieving better results than the second in some scenarios and the opposite for other ones. Any single Category A measure is able to avoid discomfort hours. For obtaining this in Present and Mid Future HWs, combinations of passive techniques are necessary. Although, during Long Future HWs, any passive measure can remove discomfort conditions inside the building.

Natural ventilative cooling achieves excellent results in the Longest and Most Intense HW of Present and satisfactory ones during the Most Severe HW of Present and the two Mid Future's HWs. In the same way of Category A technologies, during Long Future's heatwaves, the effectiveness of this measure is reduced. For this reason, combination of it with two or three other passive measure are the only configurations that obtain very good results of comfort, but, in any case, without removing discomfort hours at all.

Vapor compression refrigeration is helped by all the Category A techniques in the reduction of hot PDH. As it was seen during TMY, advanced solar shading is the technology that, combined with AC, guarantees the smaller number of discomfort hours, even better than all the three Category A measures applied with AC. The explanation for this behavior is the same of the previous paragraph.

5.3.3. Thermal survivability

In addition to comfort conditions, it is essential to verify survivability inside it during heatwaves. Results of this analysis are shown in the figures below:

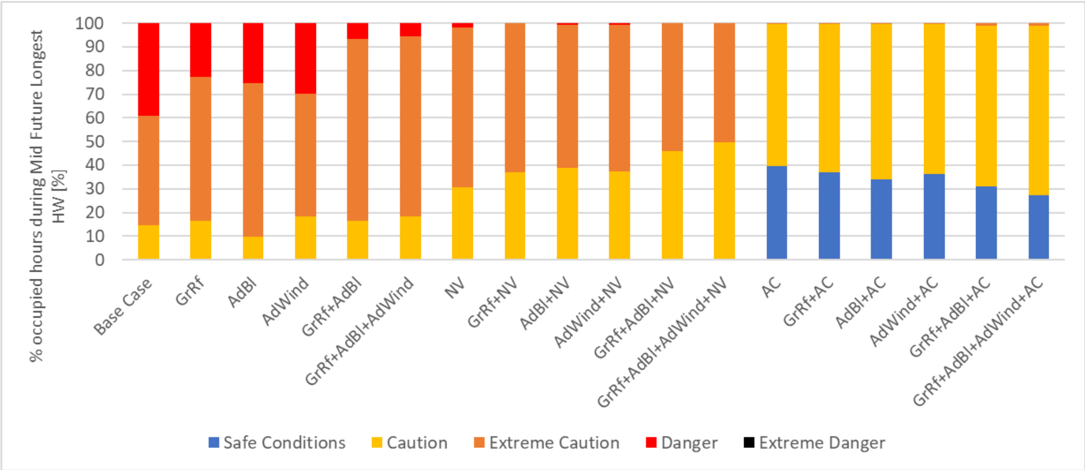


(a)

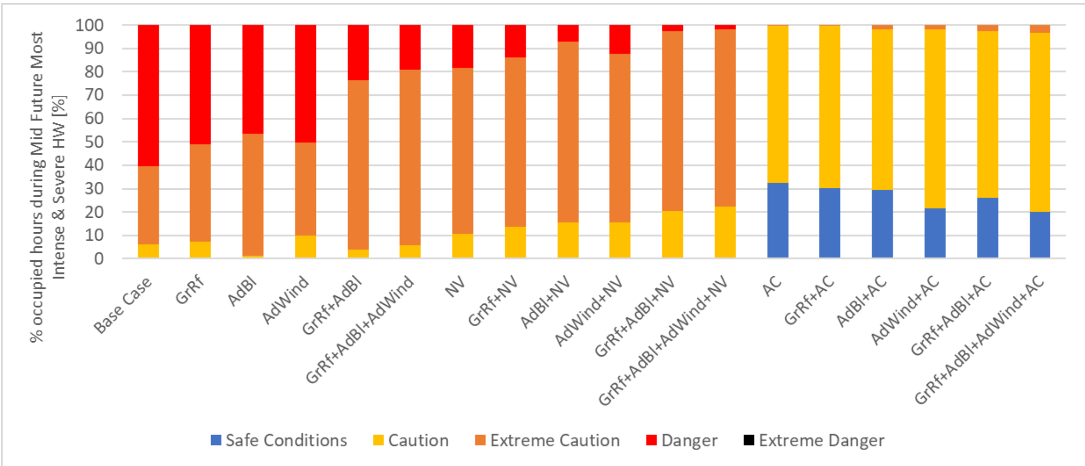
(b)

(c)

Figure 40: Survivability levels during Present (a) Longest (b) Most Intense (c) Most Severe HW

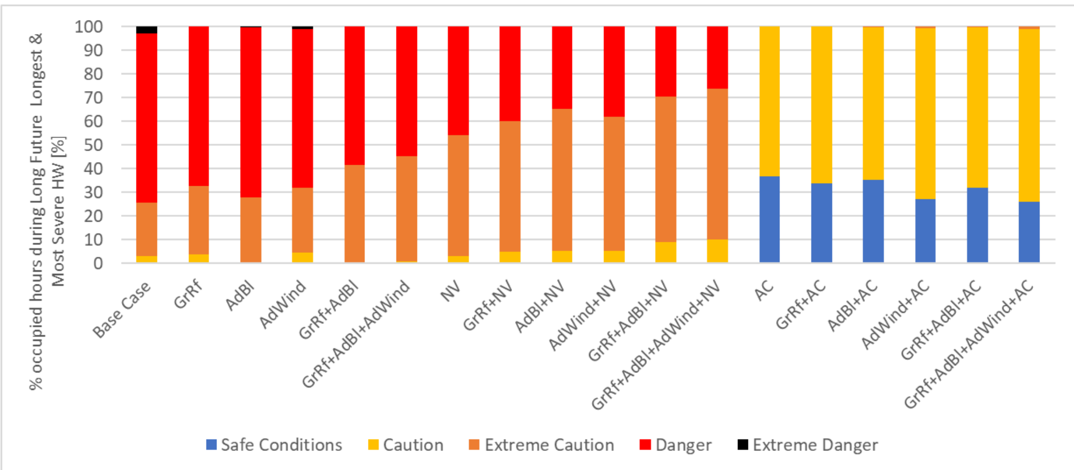


(a)

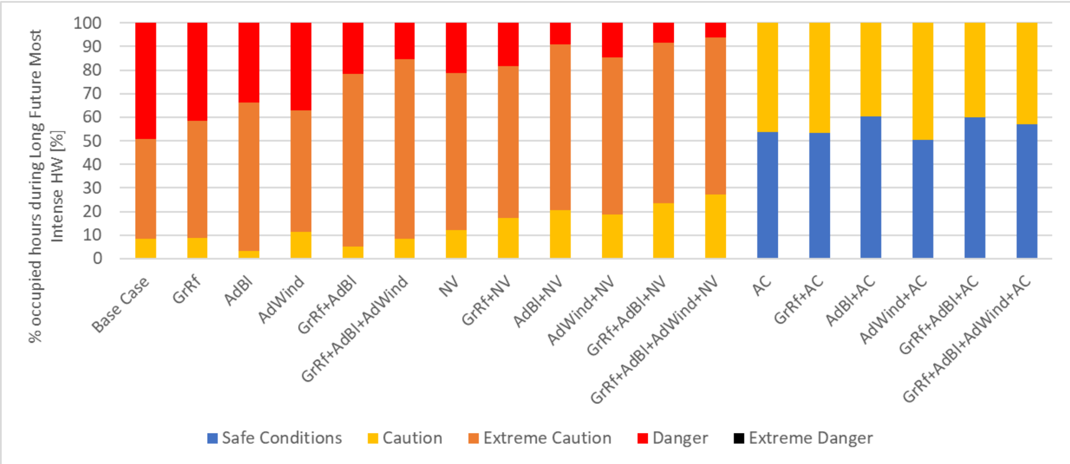


(b)

Figure 41: Survivability levels during Mid Future (a) Longest (b) Most Intense & Most Severe HW



(a)



(b)

Figure 42: Survivability levels during Long Future (a) Longest & Most Severe (b) Most Intense HW

During Present heatwaves, singular Category A techniques are not able to significantly improve comfort conditions. In fact, dangerous conditions are reduced by the technologies, but they are still present. Advanced glazing has better performance in the most severe scenarios, but it has less impact during the long periods with high outdoor temperature. On the other hand, green roof and advanced solar shading obtain good results during the periods where higher temperatures are present, reducing more dangerous conditions. Better results are obtained with the combination of two or three passive technologies. With these configurations, it is possible to avoid any dangerous states.

Natural ventilative cooling improves survivability, being able to eliminate dangerous conditions alone. For obtaining better results, at least one more passive technology can be installed. Applying ventilation, additional decrement of extreme caution conditions, during Longest, Most Intense and Most Severe heatwave, is obtained, confirming the efficacy of this measure, independently from the typology of heatwave.

Vapor compression refrigeration confirms itself as the best technology for maintaining safe conditions inside the building. In all the scenarios they are present for at least 44% of the hours, while the rest of the time is covered by caution conditions. Better performances are achieved in the longest scenario, showing that AC is more sensible to higher temperatures rather than duration of extreme period.

In Mid Future heatwaves, passive technologies are not able to remove the hours of dangerous conditions. Single Category A measures reduce them by a value between 10% and 16% during the Longest HW and 9% and 13% during the Most Intense and Severe one. Adding one technology, another 20% of reduction is achieved, whereas in case of other two, the additional decrement is lower for the longest heatwave, with maximum reduction of 25%, rather than the one obtained in the other scenario, where 32% of reduction is achieved. This result shows how behavior of each measure is a significant aspect for improvement of survivability. In fact, in this time period, a green roof is the best solution for longer events, while advanced solar shading is the most effective in case of higher temperatures.

Application of natural ventilative cooling is a good solution for increasing comfort inside the building. Combining it with two or three Category A technologies can avoid dangerous conditions during the Longest HW, but these ones are maintained during the Most Intense and Severe HW, because of the worst outdoor conditions that characterize this second heatwave.

Vapor compression refrigeration achieves worse performance respect to the present scenario, reaching only 40% of safe conditions in the first heatwave and 30% in the second one. This is caused by the highest levels of temperature and humidity that characterize heatwaves of this time period.

In the Long Future scenarios, extremely dangerous conditions in the Longest and Most Severe HW are maintained implementing only advanced solar shading and advanced glazing. For removing them, green roof or combinations of passive technologies are required. In any case, during this extremely strong heatwave, combinations of Category A techniques cannot avoid heavy heat for less than 55% of total occupied hours. Situation is less severe for the Most Intense HW, where passive measures can reduce dangerous conditions until almost 15% in case of three technologies implemented.

Natural ventilative cooling is the passive measure that reduces most dangerous conditions. Its role is essential during the Longest and Most Severe HW, reducing significantly dangerous hours, approximately of 30% respect to the other single or combined passive techniques, even if they cannot be avoided. During the Most Intense HW, reductions achieved are around 15%, but this is balanced by average better conditions inside the building compared to the ones performed in the other heatwave.

Vapor compression refrigeration maintains safe conditions for a number of hours in the range between 27% and 37% in the longest and most severe heatwave and between 50% and 60% in the other. These results are slightly better than the ones achieved in the Mid Future, because of the lower relative humidity levels that are present in this scenario and have a bigger impact than the higher operative temperatures.

5.3.4. Analysis of temperatures inside the critical thermal

As last step of the analysis of performances of the different cooling techniques during heatwave periods, it is important to visualize the conditions obtained inside the most critical zones of the building. The apartment that is investigated in this section is the left one of the 4th floor south-exposed façade, as explained in section 5.1.1.5. The heatwaves selected for this analysis are the ones with the highest AWD for each time period, the same used for simulations of power outages in the following section (5.4). Operative temperature evolution during one heatwave period for each time scenario is shown in the figures below.

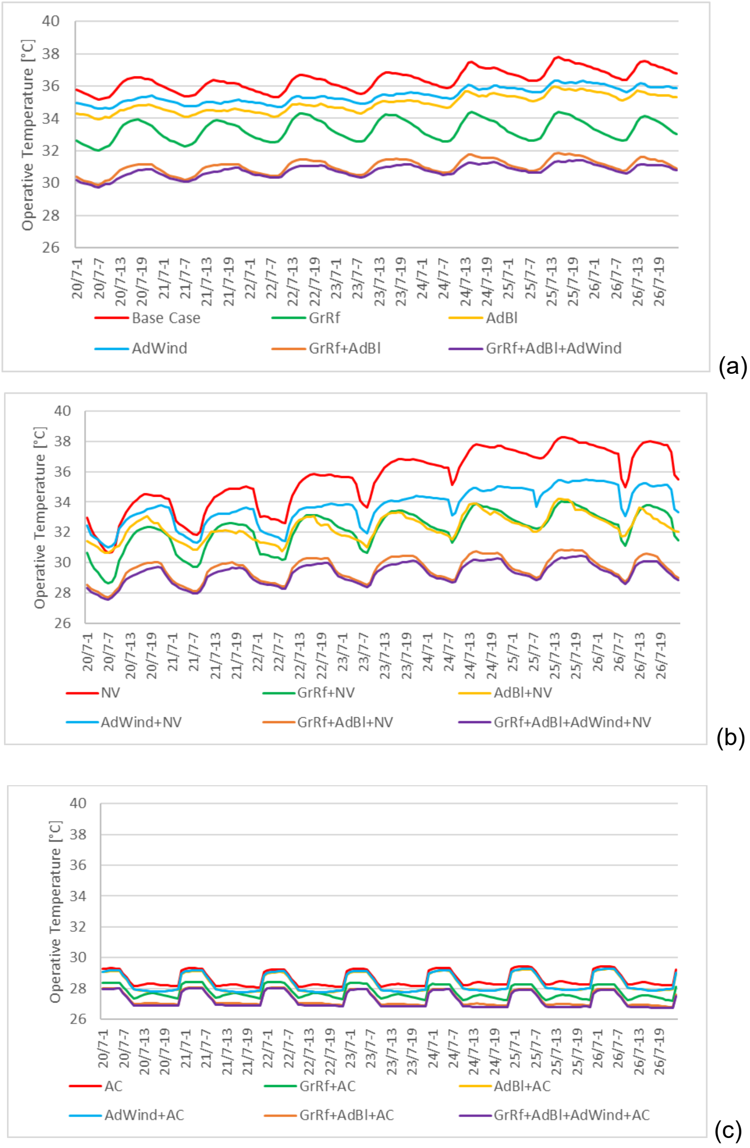


Figure 43: Operative temperature inside the most exposed apartment during Present Most Severe HW (a) without Category B measures (b) with natural ventilative cooling (c) with vapor compression refrigeration implemented

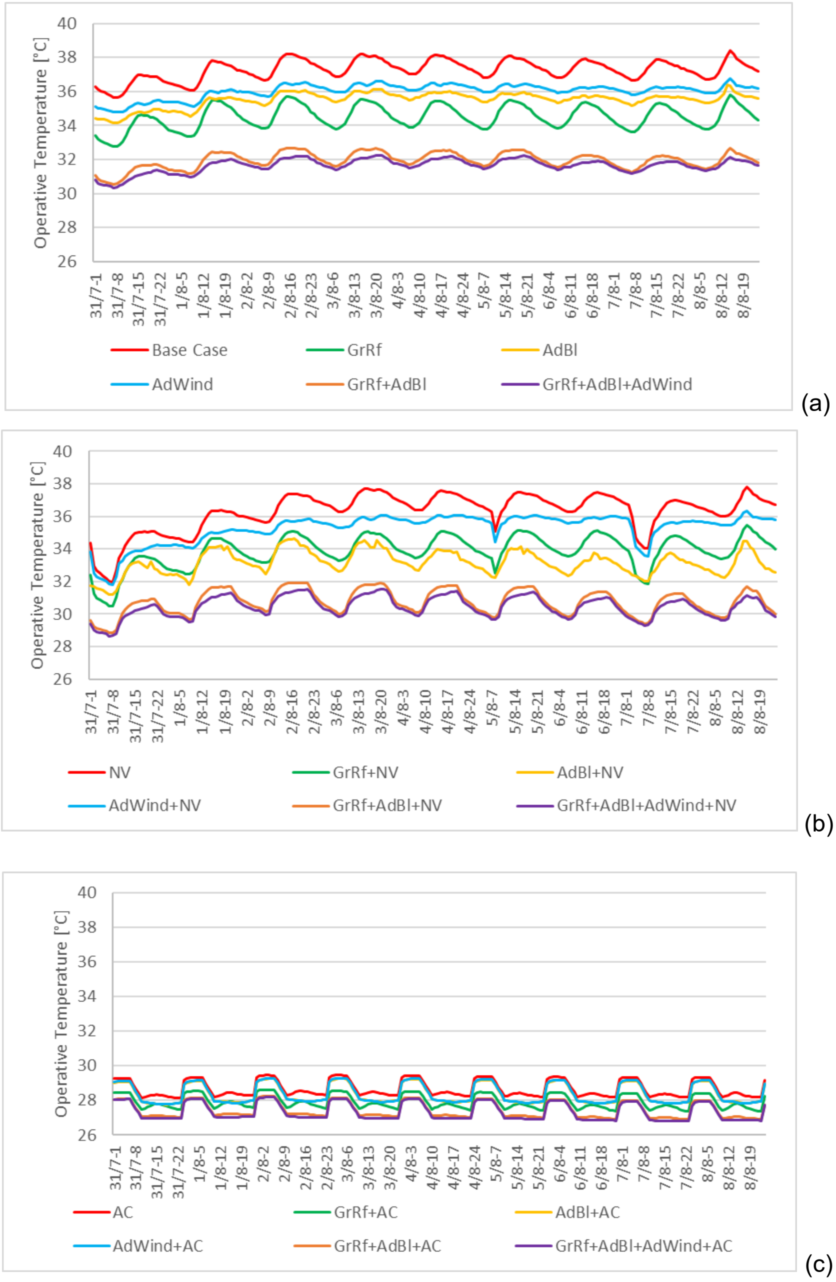
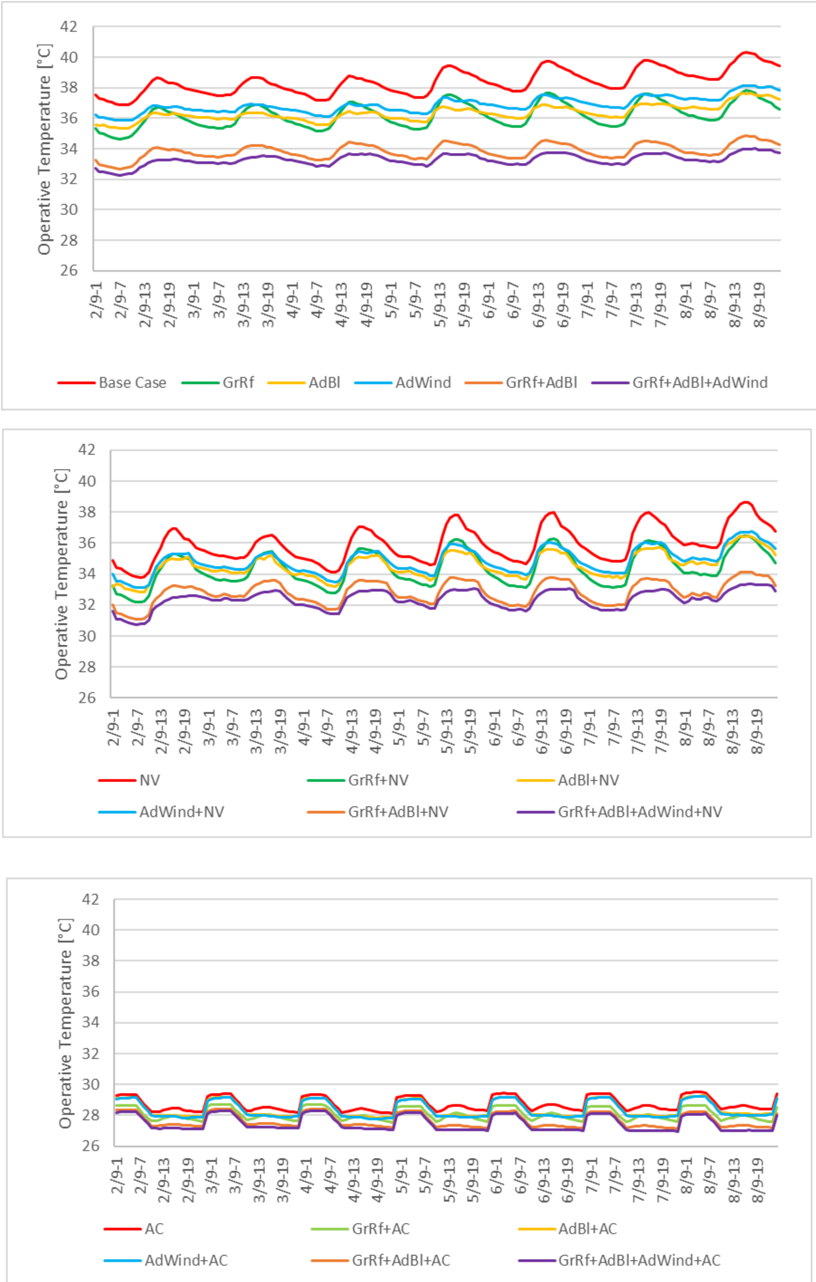


Figure 44: Operative temperature inside the most exposed apartment during Mid Future Most Intense and Severe HW (a) without Category B measures (b) with natural ventilative cooling (c) with vapor compression refrigeration implemented



(a)

(b)

(c)

Figure 45: Operative temperature inside the most exposed apartment during Long Future Most Intense HW (a) without Category B measures (b) with natural ventilative cooling (c) with vapor compression refrigeration implemented

In the scenarios without any Category B technology implemented, considerable high temperatures are reached. In the Base Cases, maximum temperatures are around 37.8 °C, 38.4 °C and 40.3 °C in the Present, Mid Future and Long Future. Average daily difference between maximum and minimum temperatures is 1.0 °C for the first two scenarios and 1.5 °C for the third.

Implementation of Category A techniques helps in the reduction of these temperatures. Green roof is a very effective technology for this apartment, increasing insulation and reducing the gains of solar radiation. Operative temperature is reduced by approximately 2.5 °C in all the scenarios and it maintains the same daily variation and dependency on outside temperature of the base case.

Advanced solar shading performs a lower reduction on inside operative temperature, of around 1.8 °C, and they also maintain a lower difference between daytime and nighttime temperatures, of approximately 0.5 °C. This last aspect is cause by lower direct solar heat gains during the day, since the fraction that should pass through the glazing is stopped by the shading equipment, but the remaining part, that arrives on the opaque zones of the envelope, is stored inside the façade and the roof and it is re-emitted during the night, maintaining a higher temperature during that time. The same results are obtained with the use of advanced glazing, that penalize thermal flux from outside to inside the apartment. This reduces temperature peaks during the day, but it cannot avoid thermal re-emission of solar gains from the cover. In addition, possible thermal losses during the night, that contributes to reducing indoor temperature, are minimized by low transmittance of this type of glazing. For these reasons, advanced solar shading and advanced glazing result less sensible to outside temperatures compared to green roof and base case building. Combination of green roof and advanced solar shading improve considerably the conditions inside the apartment, reducing temperatures respect to the base case of almost 6 °C. With these technologies, operative temperatures never exceed 32.0 °C, 32.6 °C and 34.9 °C respectively during Present, Mid Future and Long Future, with an average daily variation of 1.0 °C. Adding advanced glazing to this configuration, results are variable in the different periods. In the Present one, daytime temperature has an additional reduction of 0.5 °C and no variation during nighttime. In contrast, these differences during day and night became 0.7 °C and 0.2 °C in the Mid Future and 1.0 °C and 0.5 °C in Long Future. From these results, it is evident that the configuration with all three Category A measures is the most preferable in the latter scenarios.

Natural ventilative cooling achieves good results in reducing minimum temperatures during heatwave periods. In fact, during the nights when it is possible to be implemented, in a few hours, temperatures can be reduced up to 2.0 °C in the Present and to 2.5 °C in the Mid Future. The reduction is more significant in case of any or a single Category A technology implemented, whereas with two or three measures this reduction is lower. This behavior is in accordance with the results of the study proposed by Ji et al. (145). It is important to highlight that, in some cases, this ventilation could increase daily maximum temperatures, like it happens in some days of the Present scenario. This effect is usually compensated in the daily balance by the lower minimum temperatures, but should be reminded that it could increase discomfort during that most critical hours of the day.

Vapor compression refrigeration performs the best reductions of operative temperatures in all the scenarios. Even if air temperatures are the same for each configuration, operative ones are affected by the external gains that increase mean radiant temperatures of the surfaces. Without any passive technology implemented, operative temperature during the day remains close to the value of 28.5 °C, that is 2.5 °C higher than the set point temperature. During night, this temperature can reach the values of 29.5 °C, which exceeds for 1.5 °C the value set for that period. The installation of a green roof can reduce operative temperature of 0.5 °C during daytime and 1.0 °C during nighttime. Advanced solar shading and advanced glazing achieve the same result, but only during the central hours of the day, when the effect of measures is significant. In fact, during the first and the last daylight hours, operative temperature results higher than the one around midday. This is caused by the solar radiation during the first and the last hours of light and by the effect of re-emission during the end of the day. Implementation of another passive measure, also in this case, permits to achieve a bigger reduction of operative temperatures, of 1.0 °C and 1.3 °C during day and night, respectively. In the case where all the three Category A technologies are installed, operative temperature can be maintained almost fixed for the whole period at the temperatures of 27.0 °C for the day and 28.2 °C for the night. These values slightly vary along the different scenarios, with higher average temperatures during the future ones, caused by the more severe outside conditions.

The plots of operative temperatures in presence of vapor compression refrigeration highlight one important problem of the choice of set point temperatures for the apartments. In fact, considering the effects of thermal accumulation during the day and following re-emission during the night, during these extremely hot periods, they cause thermal discomfort during nighttime. This aspect should be taken into account in the following development of this work, since it can cause a wrong evaluation of resilience, safety and comfort levels inside the building, when this active technique is implemented.

5.4. Performance of cooling technologies during Power Outages

As last step of the analysis, it is important to visualize the behavior of the building in case of failure of the electrical grid, which unable the use of some active cooling power, such as vapor compression refrigeration. It is reminded that these events are more frequent during periods of extremely high request of electricity, that usually are coincident with heatwaves periods (93). In fact, high outside temperatures significantly decrease the performances of passive cooling systems, increasing the use of active cooling technologies, that, during these events, require big amounts of electric energy for long and continuative periods (150). As it was explained in section 3.5.3., power outages are simulated during the HW period, but simulation covers a longer period, starting five days before HW occurrence and finishing five days after.

5.4.1. Climate resistance assessment

At first, climate resistance is evaluated for the different time periods. Results obtained in case of implementation of only Category A technologies and their combination with natural ventilative cooling are presented in **Errore. L'origine riferimento non è stata trovata.**.

	Present Most Severe HW			Mid Future Most Intense&Severe			Long Future Most Intense HW		
	IOD	AWD	α	IOD	AWD	α	IOD	AWD	α
Base Case	4.58	10.48	**0.44**	5.74	11.37	**0.50**	6.15	14.26	**0.43**
GrRf	3.98	10.48	**0.38**	4.60	11.37	**0.40**	5.35	14.26	**0.37**
Bl	3.51	10.48	**0.33**	4.55	11.37	**0.40**	5.04	14.26	**0.35**
AdWind	4.22	10.48	**0.40**	4.65	11.37	**0.41**	4.99	14.26	**0.35**
GrRf+AdBl	2.24	10.48	**0.21**	3.36	11.37	**0.30**	4.12	14.26	**0.29**
GrRf+AdBl+AdWind	1.99	10.48	**0.19**	3.05	11.37	**0.27**	3.65	14.26	**0.26**
NV	3.63	10.48	**0.35**	4.73	11.37	**0.42**	5.74	14.26	**0.40**
GrRf+NV	3.15	10.48	**0.30**	3.93	11.37	**0.35**	5.12	14.26	**0.36**
AdBl+NV	2.81	10.48	**0.27**	3.84	11.37	**0.34**	4.82	14.26	**0.34**
AdWind+NV	3.23	10.48	**0.31**	3.87	11.37	**0.34**	4.75	14.26	**0.33**
GrRf+AdBl+NV	1.85	10.48	**0.18**	2.97	11.37	**0.26**	4.07	14.26	**0.29**
GrRf+AdBl+AdWind+NV	1.63	10.48	**0.16**	2.69	11.37	**0.24**	3.63	14.26	**0.25**

Table 23: Climate resistance indicators in case of PO during Present Most Severe, Mid Future Most Intense and Severe, Long Future Most Intense HW

Visualizing the values of α of the three periods characterized by power outages, they result always lower than 0.5, confirming the climate resistance of the building in case of this kind of disrupting event. In case of a single Category A technology implemented, resistance indicator is lower than the one of base case, with the maximum reduction of 0.11 performed by advanced solar shading during the Present HW. Among the three techniques, this one guarantees the best results in all the scenarios. Implementing another measure resistance is improved, but in this case the reductions are more dependent on the time period, being equal to 0.19, 0.09 and 0.06 for the Present, Mid Future and Long Future respectively. The installation of the third technology does not reduce α in a significant way, with the maximum reduction of 0.3 in the future scenarios.

Using natural ventilative cooling slightly improve climate resistance of the building, but its performance is reduced moving through the years, because of the more severe outdoor conditions. During the Present scenario, its use is very advantageous, especially in case of implementation together with three other passive technologies, where is possible to obtain a α value equal to 0.16.

Comparing the indicators of this case of power outages with the ones obtained for the same heatwaves but without any active technology in the building, shown in Table 22, it is noticeable how vapor compression refrigeration helps in the maintenance of better conditions inside the apartments. In fact, thanks to the presence of better average conditions before the occurrence of power outages, overheating is reduced respects to buildings without any active measure installed. In particular, IOD results 0.2 °C for the configuration with only Category A measures and 0.1 °C for the ones with also NV implemented. Consequently, the building is more resistant to heatwaves in case of power outages.

5.4.2. Discomfort hours

Considering the results obtained in the climate resistance assessment, it is predictable that comfort conditions are maintained for a longer period respect to the previous case presented in chapter 5.3.2. Values of HDDH for the three scenarios are shown in Figure 46.

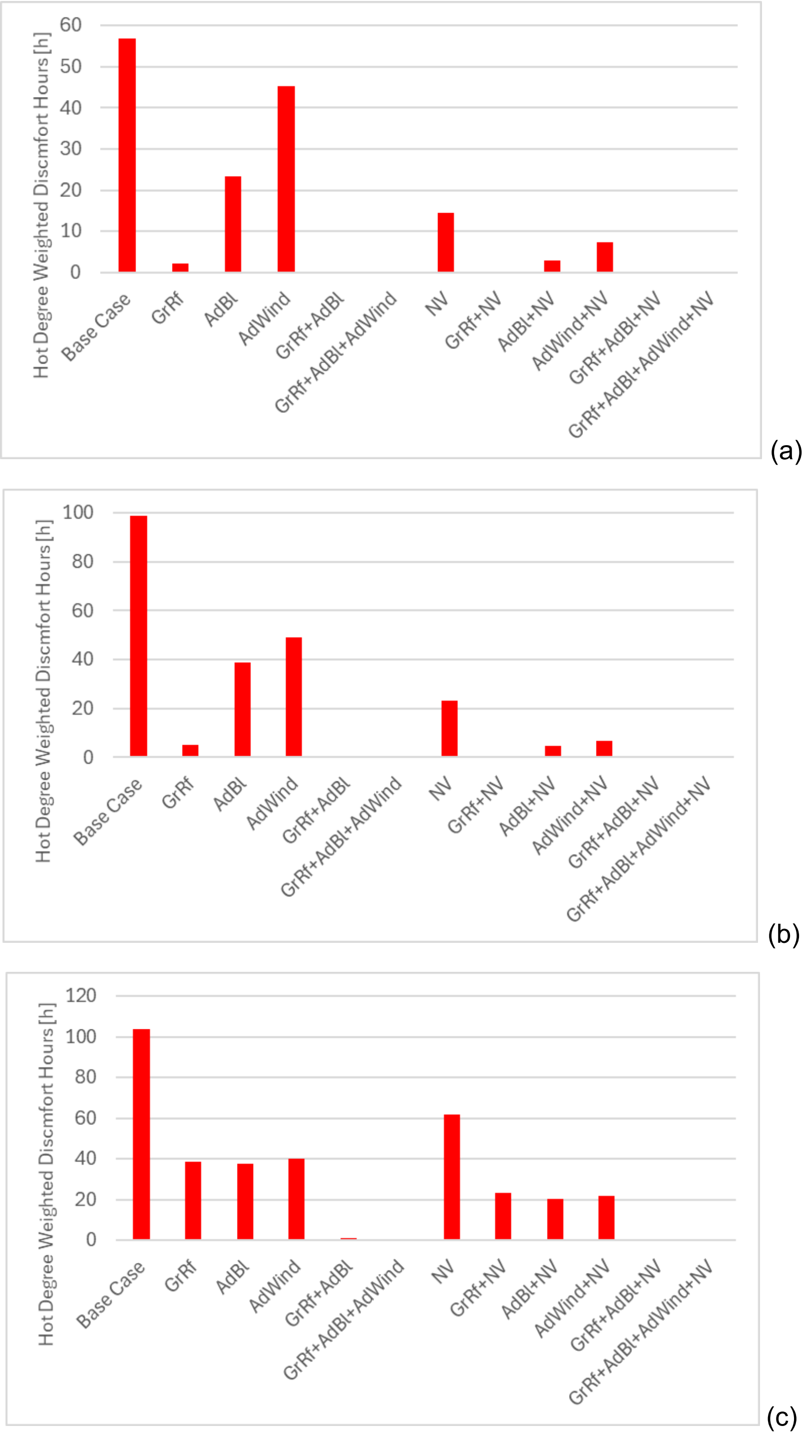


Figure 46: Hot Degree weighted discomfort hours during (a) Present Most Severe (b) Mid Future Most Intense&Severe (c) Long Future Most Intense HW for the different passive cooling technologies implemented

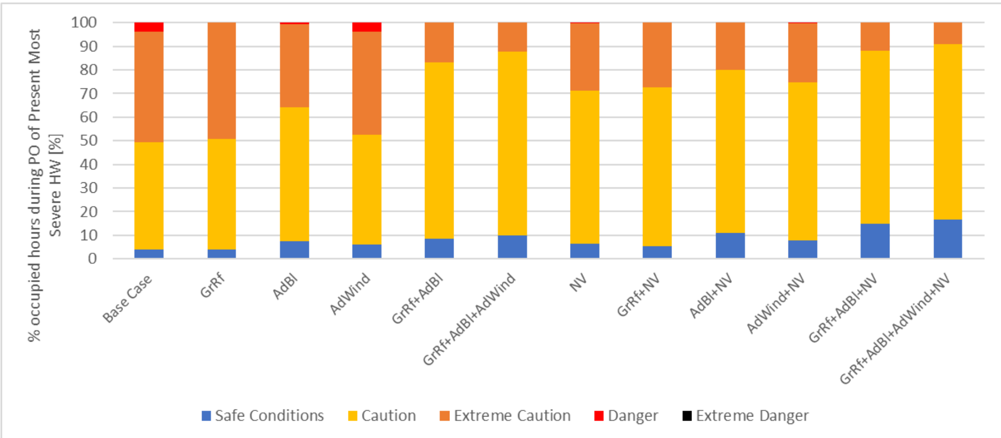
Like in the previous case, the amount of discomfort hours increases moving through the scenarios. During Present HW, the single green roof performs a very important reduction of HDDH, passing from 56.8 h of the base case to 2.2 h. On the other hand, advanced solar shading and advanced glazing reduce discomfort hours, but not in a considerable way. Natural ventilative cooling also is a valid solution for reducing discomfort inside the dwelling, especially combined with other passive measures.

Similar results are calculated for Mid Future HW, in terms of percentual reduction. In fact, effectiveness of passive techniques is analogous to the Present scenario, with slightly higher values caused by higher outdoor temperatures.

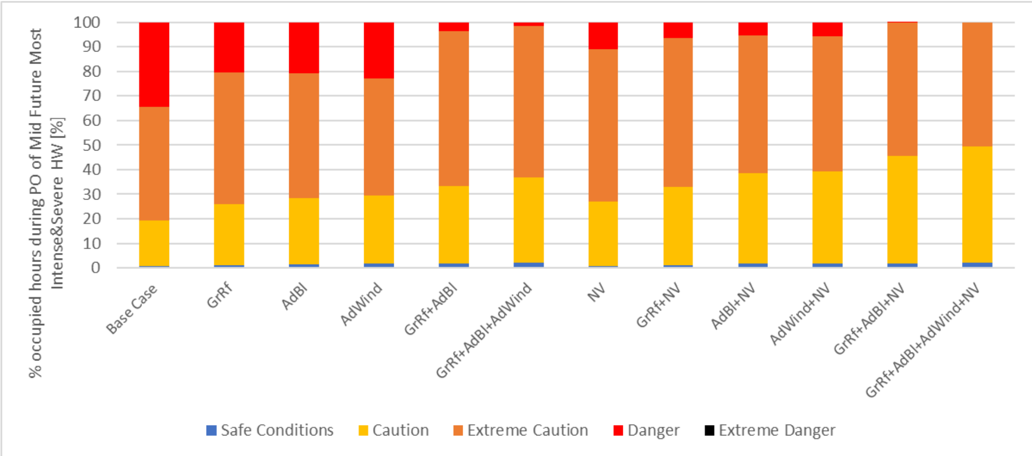
During Long Future HW, performance of single Category A technology is almost the same. Results obtained with advanced solar shading and advanced glazing during this HW are even better than the ones of Mid Future. This aspect highlights the dependency resilience of the building not only by average higher temperatures, but also on the specific characteristics of the event. Natural ventilative cooling cannot avoid discomfort hours combined with only one other passive technique, as in the other two time periods. For this reason, its implementation with two or three Category A technologies is recommended for remove discomfort hours.

5.4.3. Thermal survivability

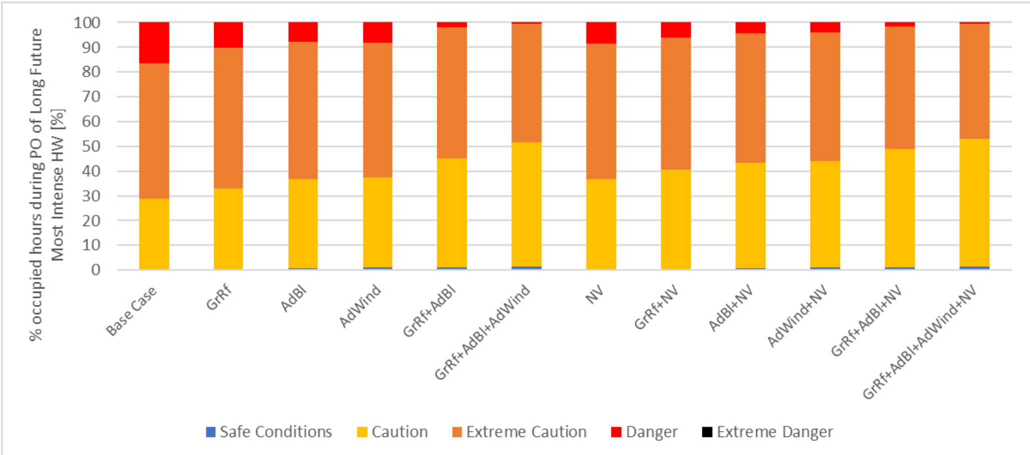
In the following step of the analysis, safety and comfort conditions during occupied hours are verified. For each time period, conditions are evaluated during the whole extreme weather period (figures on the left) and the hours of electricity unavailability (figures on the right). Results of survivability and thermal discomfort are shown in the following figures.



(a)



(b)



(c)

Figure 47: Survivability levels in case of Power Outages occurring during the (a) Present Most Severe (b) Mid Future Most Intense&Severe (c) Long Future Most Intense HW

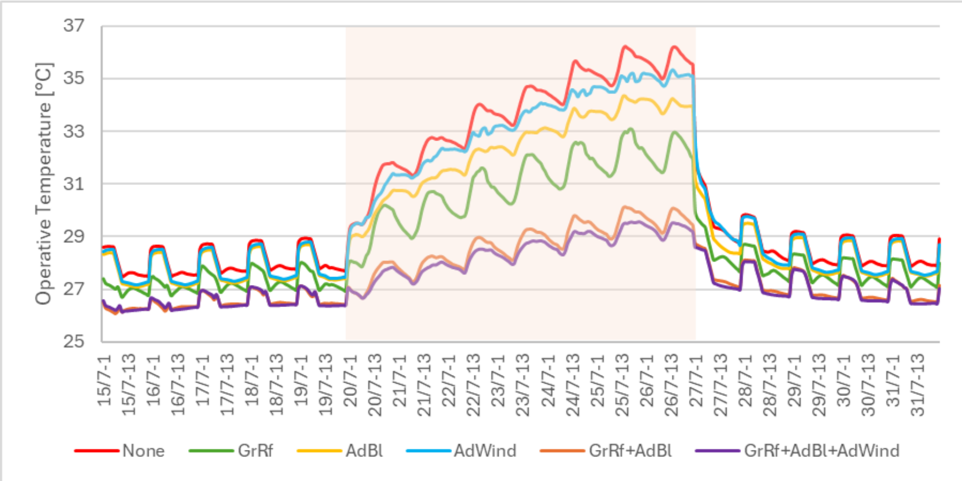
For the Present, safe conditions represent a small part of the occupied hours, less than 10%, while rest is covered principally by caution and extreme caution conditions. Dangerous conditions are present only in case of any passive measure or advanced glazing installed. The implementation of two or three Category techniques, as well as natural ventilative cooling, significantly reduce extreme caution hours. The Category B solution also increase safe conditions during the occupied period, until the value of 17%.

In the Mid and Long Future HWs, passive technologies found difficulties in avoiding dangerous conditions, that are experienced in most of the possible configurations. On the other hand, in case of natural ventilative cooling combined with two or three other measures, percentages of these conditions are set to zero.

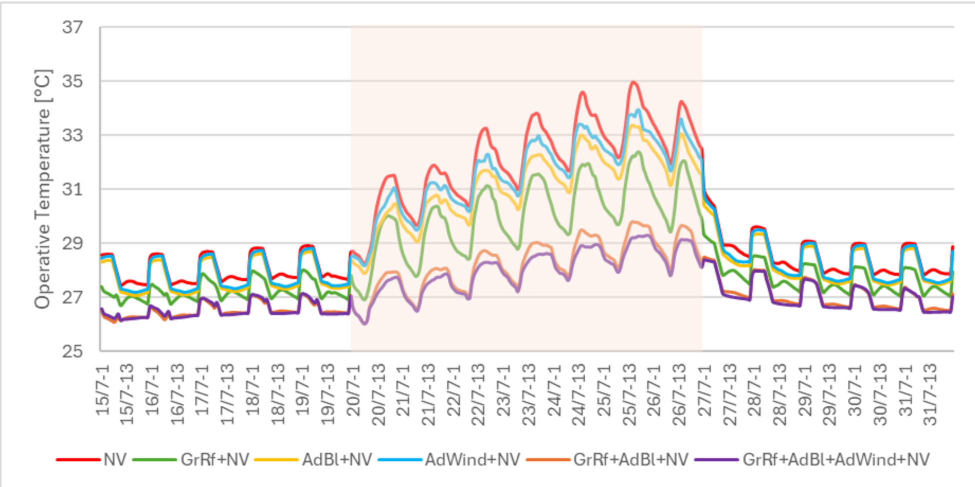
It is important to notice that, like for the other indicators, survivability levels present values that are slightly more acceptable than the ones found for buildings without mechanical conditioning systems.

5.4.4. Analysis of temperatures inside the critical thermal zones

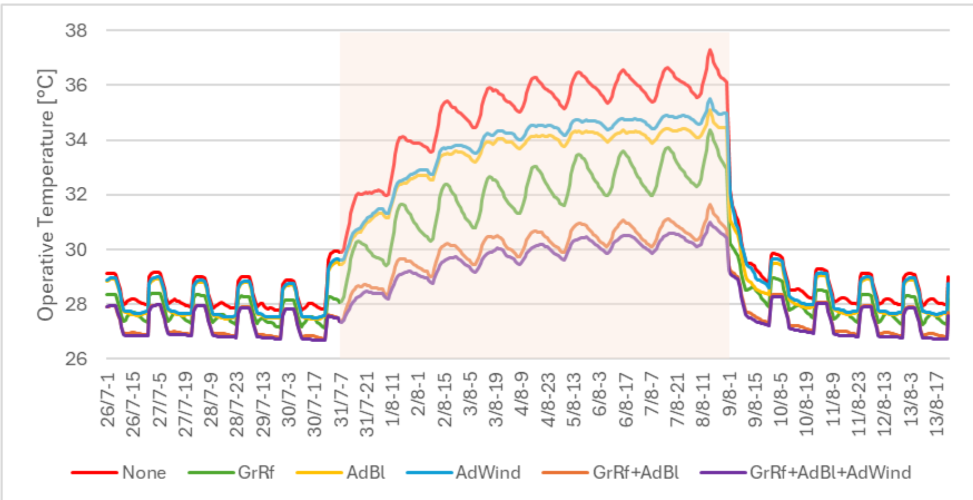
After the evaluation of survivability and comfort at whole building scale, it is important to verify the effect of measures on the most critical zones. Operative temperatures inside the 4th floor south-exposed apartment are visualizable in the figures below.



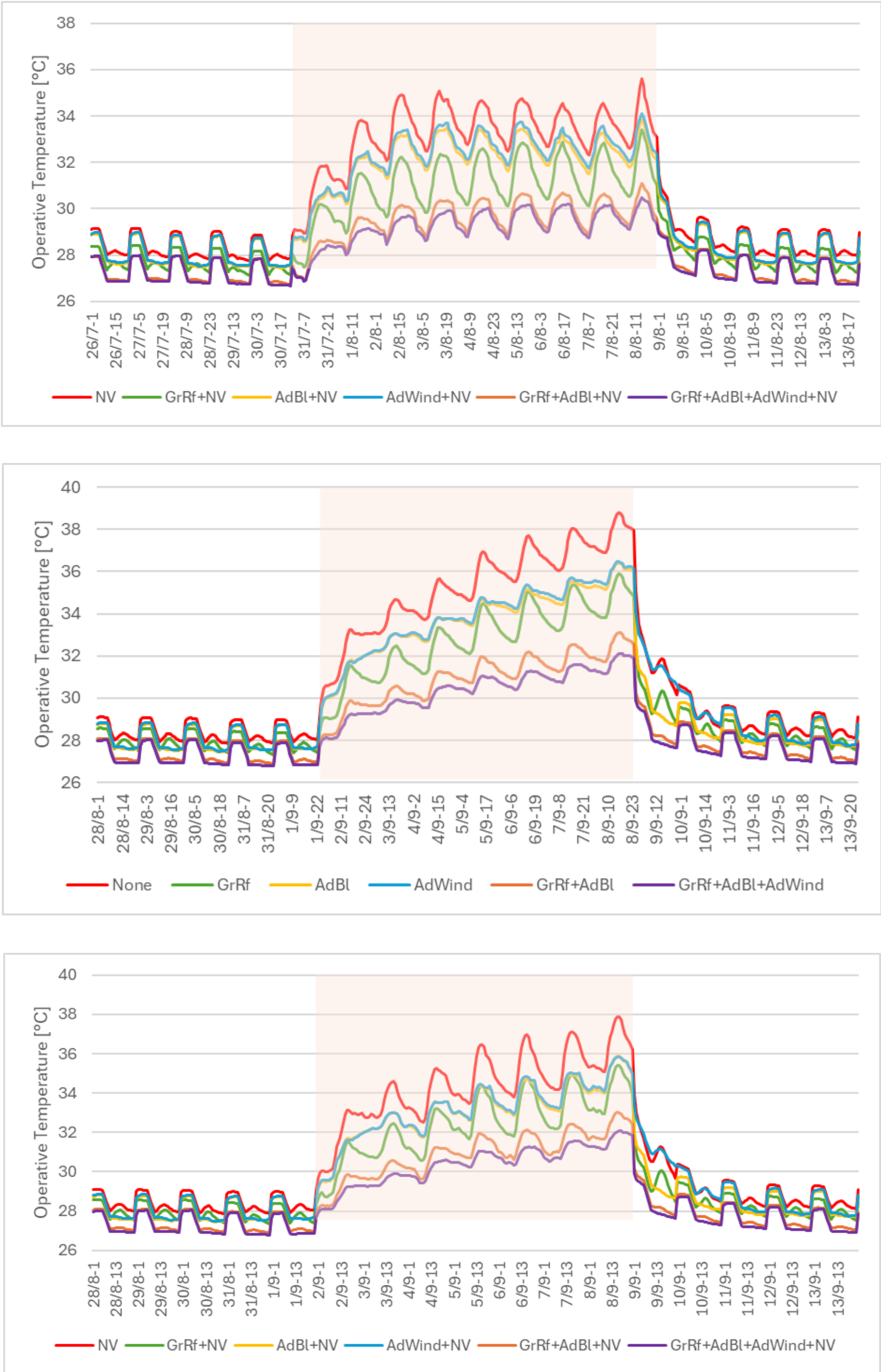
(a1)



(a2)



(b1)



(b2)

(c1)

(c2)

Figure 48: Operative temperature inside most exposed apartment in case of PO during (a) Present Most Severe (b) Mid Future Most Intense and Severe (c) Long Future Most Intense HW

Looking at Figure 48, it is evident that temperatures obtained are strongly dependent on the outside conditions and the technologies applied.

In case of any measure implemented, temperatures reach the highest values equal to 36.2 °C, 36.9 °C and 38.8 °C, in Present, Mid Future and Long Future respectively. These values are extremely higher than the ones maintained during normal operation of vapor compression refrigeration and they demonstrate the dangerousness of this kind of events. Green roof is able to reduce temperature by almost 3.0 °C, while advanced solar shading and advanced glazing perform lower reductions, around 2.2 °C for the first and 15 °C for the second. Green roof combined with advanced solar shading permits a temperature decrease of approximately 5.5 °C respect to the base case, whereas this value is enriched by an additional reduction of 0.7 °C implementing also advanced glazing.

Natural ventilative cooling significantly contributes to the maintenance of lower operative temperatures, until 2.0 °C for Present and Mid Future HW and 1.0 °C for the Long Future one. Important reductions of temperature are performed during nighttime, especially for the first two time periods.

An important aspect that should be visualized is the recovery time of usual conditions after the disrupting event. Only vapor compression refrigeration has a proper capacity of restoration of normal conditions, but passive technologies can help it in this work, reducing external thermal gains. The configurations with two and three techniques easily recover conditions, both combined and not with natural ventilative cooling, requiring them after approximately one day. On the other hand, single measures have more difficulties, especially in the latter scenarios, restoring the original conditions even two full days after the periods of power outages. Configurations with green roof and advanced solar shading present a faster recovery than the one with advanced glazing, especially when this last one is implemented without natural ventilative cooling.

6. Results of energy needs, environmental and economic analysis

After the assessment of climate resistance, comfort and survivability inside the building implementing different cooling technologies, it is important to evaluate their performances in terms of energy savings, impact on the environment and costs.

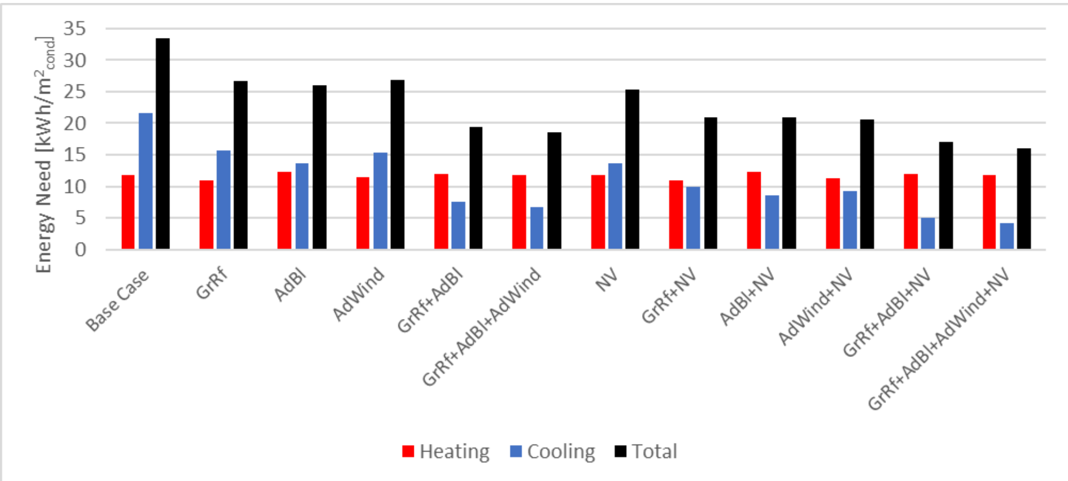
Cooling and heating needs is evaluated for the TMY, to visualize how techniques would impact on them. Values that are found would be useful for future implementation of thermal equipment in the apartments, chosen and sized basing on this analysis. This evaluation is made considering ideal air loads in EnergyPlus.

Vapor compression refrigeration demand is not compared with the one of other measures, since its request is not thermal energy, but electrical energy, necessary for the correct work of the machine. Its needs are calculated during the TMY and the HWs studied in the previous paragraph, the ones with the highest AWD in each period. In this way, it is possible to evaluate energy and primary energy reductions, impact on CO_2 emissions and economical savings.

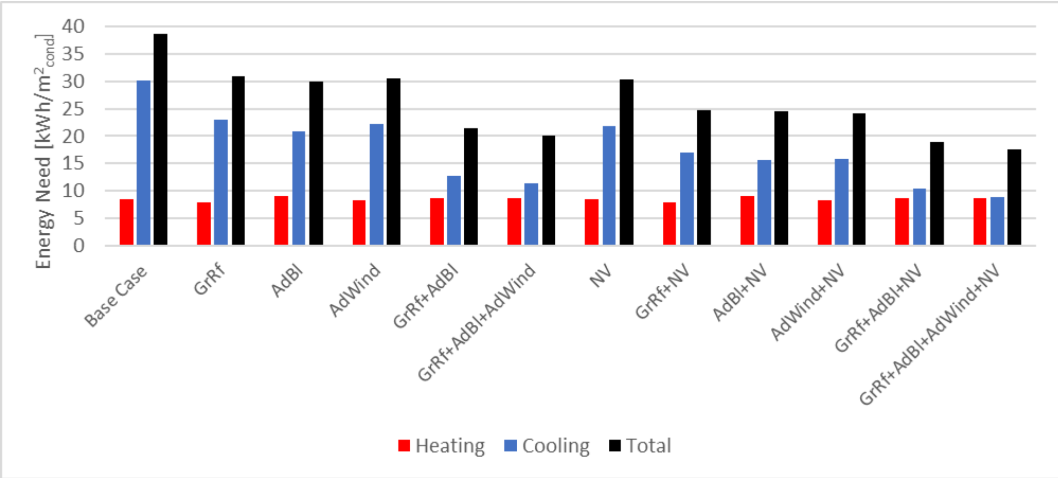
It is important to highlight that vapor compression refrigeration would cover only the cooling need of the building. Heating need is satisfied by any equipment in this model.

6.1. Energy Needs during TMY

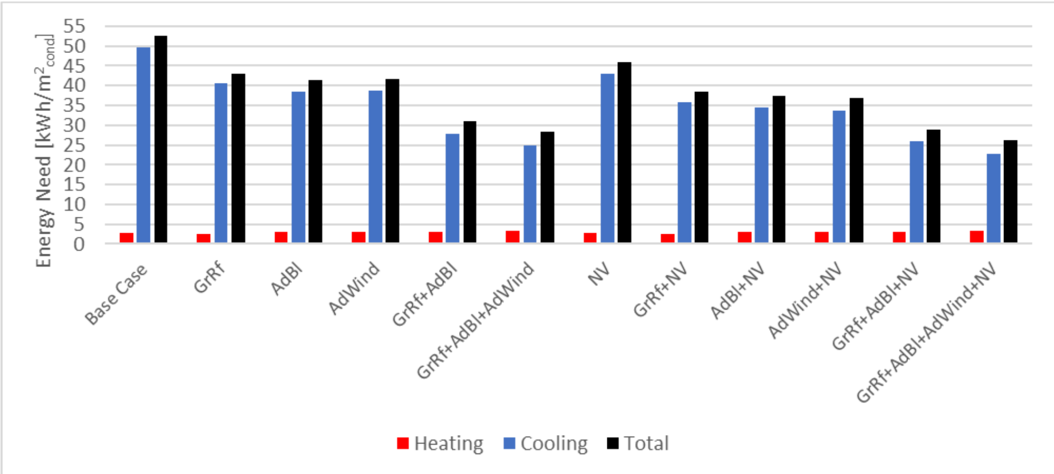
The first aspect that is investigated is the modification of the energy needs with the implementation of the different technologies. Annual heating, cooling and total energy needs during the different periods are shown in Figure 49.



(a)



(b)



(c)

Figure 49: Heating, Cooling and Total Energy Needs during (a) Present (b) Mid Future (c) Long Future TMY

In all the scenarios, cooling technologies succeed in reducing cooling and total energy needs of building. Absolute variations increase moving through the years, achieving values up to 26.9 kW/m^2_{cond} in the latter scenario, when several techniques are applied. As explained in chapter 5.1.1.1, climate change significantly modifies building needs, reducing heating needs and increasing cooling ones. Total needs are also affected by warmer outdoor conditions, that cause its incrementation. Despite the presence of cooling measures, differences between the scenarios result significant, being minimum total energy needs equal to 16.0 kW/m^2_{cond}, 17.5 kW/m^2_{cond} and 26.2 kW/m^2_{cond} respectively during Present, Mid Future and Long Future TMY.

From Figure 50 can be seen how the ratio between cooling and heating needs is modified by the different techniques.

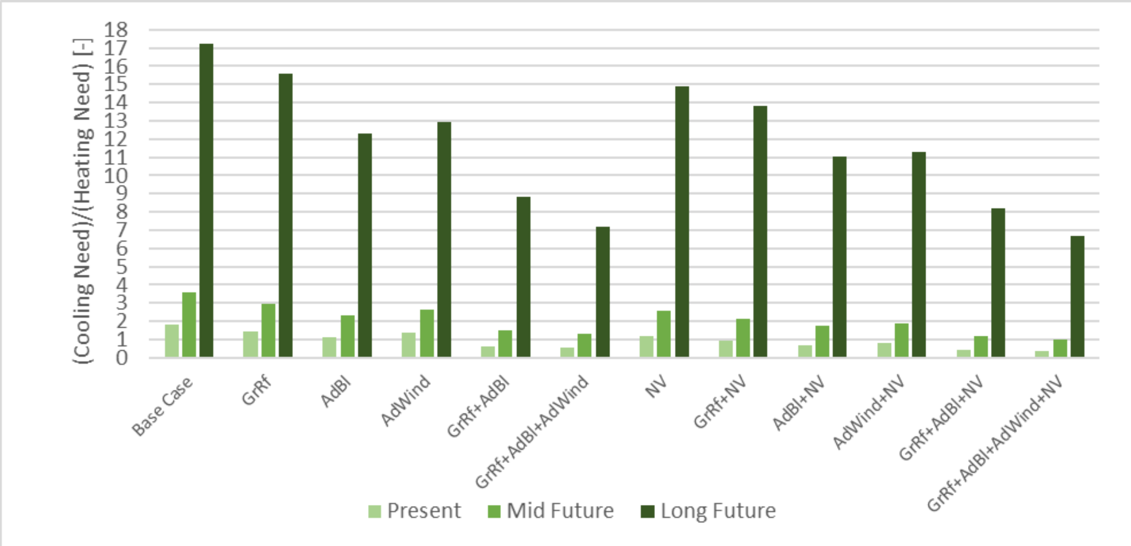


Figure 50: Cooling Need/Heating Need ratio for Present, Mid Future, Long Future TMY

For the Present scenario, whenever more than one Category A technology is implemented, cooling need results higher than the heating one. Implementing two or three technologies with natural ventilative cooling, the ratio becomes lower than 0.5, corresponding to a heating need bigger than the double of the cooling one. These numbers highlight the importance of heating need in this scenario and the cooling power of the implemented technologies. In the Mid Future cooling need is always higher than the other, especially in absence of ventilation and with only one Category A measure installed. This parameter, in any case, is always between 1.0 and 3.6, confirming the slightly higher importance of cooling rather than heating. In Long Future, values for this division are extremely pending on the cooling part, achieving values lower than 10 only when two or more Category A technologies are implemented.

Percentual variations of energy needs respect to the Base Case, provided by the different cooling technologies, are presented in the figures below.

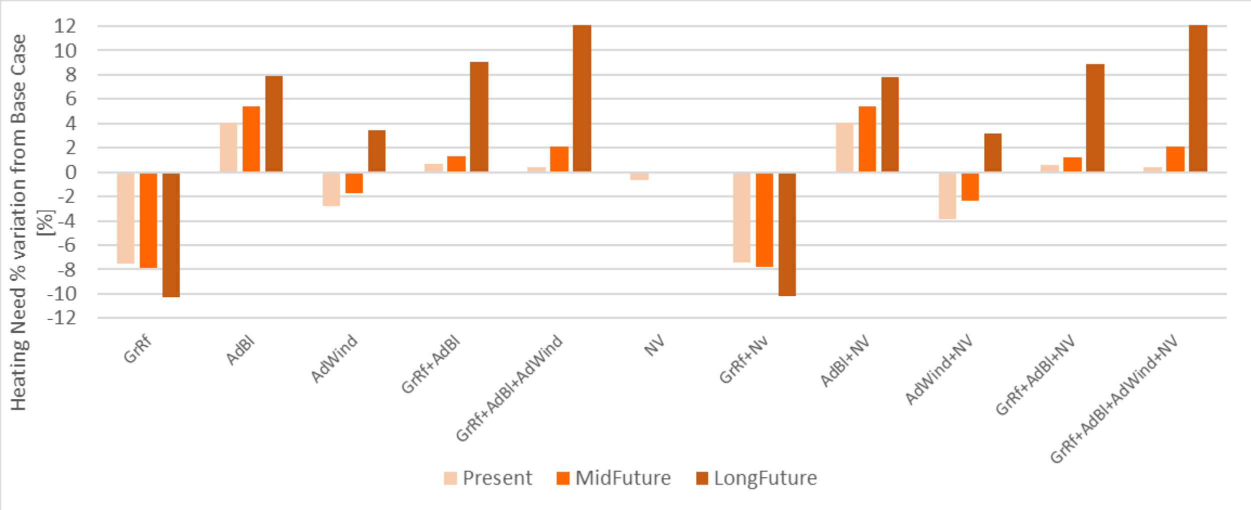


Figure 51: Heating Need Percentual Variation from the Base Case during TMY

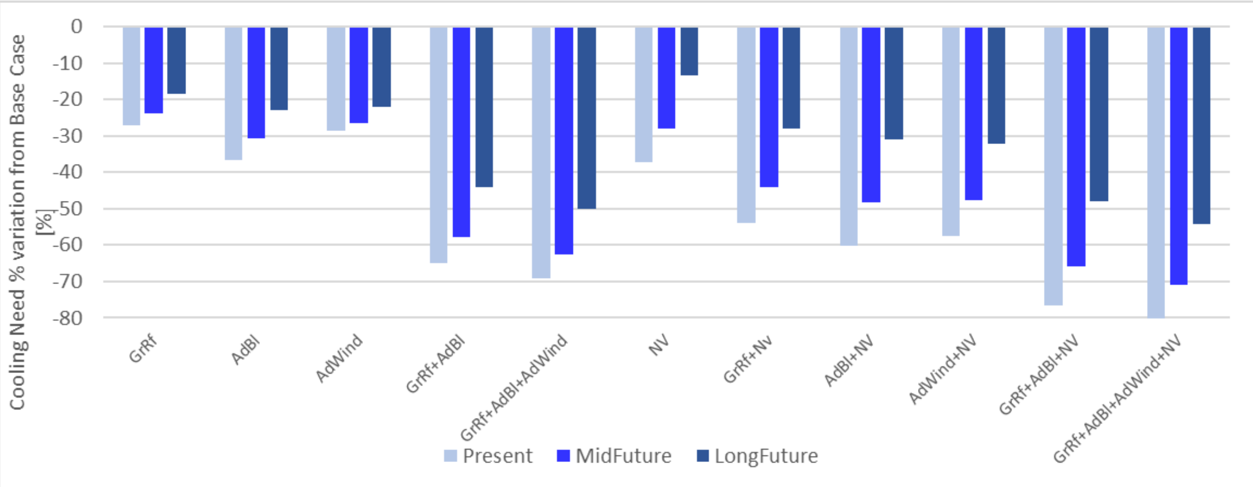


Figure 52: Cooling Need Percentual Variation from the Base Case during TMY

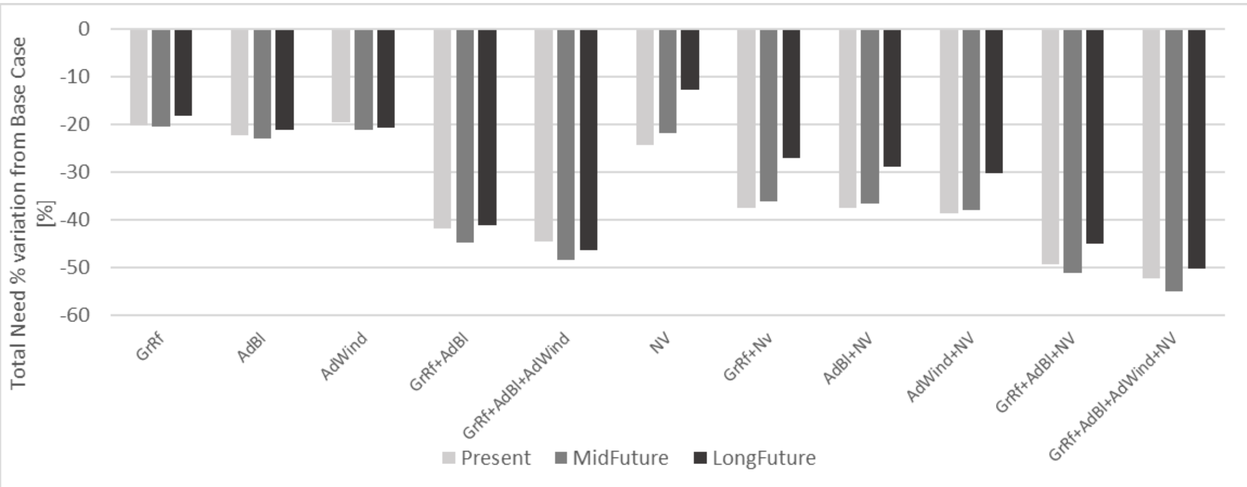


Figure 53: Total Needs Percentual Variation from the Base Case during TMY

From Figure 52 it is possible to confirm that all the cooling technologies act well, reducing cooling need of the building. It is evident that they perform better in case of more suitable scenarios, like the Present one, reducing more the need of the Base Case. Between the three single Category A technologies, advanced solar shading is the one that obtained the best results, especially during Present. This is easily explained, considering that it acts only on the direct solar radiation that enters inside the apartment, but it does not have any control on the radiation that arrives on the opaque surfaces, with the consequent effect of storage inside the envelope and re-emission inside. It cannot significantly reduce heat conduction created by temperature difference between outside and inside environments. Green roof is the less effective and its performance also decreases more along the scenarios. Averaging results of the three single technologies, reductions for Present, Mid Future and Long Future are around 31%, 27% and 21% respectively. Combinations of Category A technologies significantly improve the needs of the building, acting on more zones of the envelope at the same time. In case of two technologies implemented, cooling need is approximately 34%, 31% and 23% lower compared to the cases with one technology, for the Present, Mid Future and Long Future scenarios respectively. Implementing three technologies at the same time, percentages of additional reduction increase by 5%, arriving to 35%, 32% and 27%. Also in these cases, reductions decrease along the years.

Natural ventilative cooling achieves good results for Present scenario, decreasing cooling need by 37%, and Mid Future, with 28% of reduction, respect to Base Case. However, it is less effective in Long Future, reducing need by only 13%. This is caused by higher average outside temperatures, that increase temperature of air infiltrations, that have, consequently, less cooling power, and reduces the hours where outside temperatures are lower than 26 °C, limiting the use of this kind of ventilation. Using this technology with the passive others, very satisfactory results are obtained. Respect to the Base Case, a single Category A technique combined with natural ventilative cooling can reduce cooling need of approximately 60% for Present, 47% for Mid Future and 30% for Long Future. Percentages increase of 10% implementing one more passive technology and 20% implementing two more.

Since technologies are implemented in the envelope of the building and they cannot be removed, it is also important to evaluate their impact during the heating season.

Advanced solar shading increases annual heating need. This is related to some inaccuracy in the model simulations. Advanced solar shading is activated when indoor temperature is higher than 25 °C. Increments of heating needs can be related to their incorrect use during intermediate periods. In some hours of the year, it could happen that indoor temperature is close to 25 °C, while outdoor temperature is significantly lower than 25 °C. In this situation, solar gains cannot contribute to the maintenance of a comfortable temperature for middle seasons, reducing it to a value that is lower than 20 °C, increasing the heating need.

Green roof is the only technology that reduces heating need in all the scenarios. This is due to its action in the part of the building most exposed to transmission losses. Its performances increase along the scenarios. This effect can be explained considering that, in the future, heating need would be present for less days of the year, with also a lower average value. In this way, any reduction on it results more significant respect to Base Case, having every single day more importance on the heating need. In fact, in terms of absolute values, green roof decreases need of 0.88 kWh/m^2_{cond} for the Present scenario, of 0.67 kWh/m^2_{cond} for the Mid Future and 0.30 kWh/m^2_{cond} for the Long Future. Advanced glazing, indeed, reduces heating need in Present and Mid Future, of 2.8% and 1.7%, but it does the opposite in Long Future, with an increase of 3.5%. The reason for this result can be found in the effect of reduction of both transmission losses and solar heat gains inside the apartments. The first effect helps in the reduction of the need, while the second penalizes it. In Long Future, considering the higher outside temperatures, the favorable reduction of thermal flux to the ambient is less important than the unfavorable penalization of solar gains contribution, so heating need is globally increased. The combination of green roof and advanced solar shading achieves results that are, better than the single shading system, but worse than the single vegetative roof. Adding advanced glazing to them, heating need reduction is improved for Present and Mid Future, but it is converted in a higher need respect to the Base Case for Long future. In this last case, the global increase of heating need caused by advanced solar shading and new glazing is higher than the reduction provided by green roof.

Natural ventilative cooling does not affect the heating demand, confirming the goodness of the criteria of use of this technology during the year.

In terms of total energy need during the year, all the technologies help in reducing it, especially when they are combined. Green roof, advanced solar shading and natural ventilative cooling perform better in the Present scenario, whereas advanced glazing is more suitable for the future ones. When they are combined, there is not a scenario where the best performance is achieved, since it depends on the number of technologies and their effect on heating and cooling over the years.

6.2. Energy, Emissions and Economical Savings

In this section, the use of an electrical equipment, vapor compression refrigeration, installed in the apartments for satisfying cooling need is considered. In this way, it is possible to evaluate savings in terms of electricity consumption, primary energy, CO_2 emissions and money.

6.2.1. Evaluated factors and prices

Essential elements for the evaluation of savings are factors and prices of each scenario, that enable the calculation of the different magnitudes. They are evaluated using the methodology presented in section 3.4.3. Final factors and prices are presented in the table below:

	Primary Energy factor [kWh/kWh]	CO2 Emission factor [kg-eq/kWh]	Annual Price [€/kWh]	Summer HWs Price [€/kWh]
Present	2.368	0.331	0.063	0.067
Mid Future	1.719	0.061	0.056	0.058

Table 24: Primary Energy and Emissions factors and Annual and Summer HWs Prices

It is noticeable how the new decarbonization plans would reduce primary energy consumption and carbon emissions for electricity. However, factors and prices for the future are only an estimation in absence of studies or plans for those years. In fact, it should be mentioned that, if real future configurations for electricity production would present a higher cover of renewable sources, results of this work of primary energy request, CO_2 emissions and the relative saving would be overestimated.

6.2.2. Reductions during TMY

Electricity consumption, PE demand, carbon emissions and cost related to the use of vapor compression refrigeration in the building during TMY, for each different passive measures implemented and time period, are shown in Table 25.

Present TMY								
Passive Technology Implemented	Electricity Comsumption [kWh/m^2]		Primary Energy Demand [kWh/m^2]		CO2 emissions [kg-eq/m^2]		Costs [€/m^2]	
	Total	Reduction	Total	Reduction	Total	Reduction	Total	Reduction
None	7.63	0.00	18.07	0.00	2.53	0.00	0.48	0.00
GrRf	5.60	-2.03	13.27	-4.80	1.85	-0.67	0.35	-0.13
AdBl	5.96	-2.36	14.12	-3.94	1.97	-0.55	0.38	-0.11
AdWind	5.40	-2.23	12.78	-5.29	1.79	-0.74	0.34	-0.14
GrRf+AdBl	3.94	-4.69	9.32	-8.75	1.30	-1.22	0.25	-0.23
GrRf+AdBl+AdWind	3.00	-5.04	7.10	-10.97	0.99	-1.53	0.19	-0.29

(a)

Mid Future TMY								
Passive Technology Implemented	Electricity Comsumption [kWh/m²]		Primary Energy Demand [kWh/m²]		CO2 emissions [kg-eq/m²]		Costs [€/m²]	
	Total	Reduction	Total	Reduction	Total	Reduction	Total	Reduction
None	10.87	0.00	18.69	0.00	0.67	0.00	0.61	0.00
GrRf	8.35	-2.52	14.36	-4.33	0.51	-0.15	0.47	-0.14
AdBl	7.83	-3.04	13.46	-5.23	0.48	-0.19	0.44	-0.17
AdWind	7.94	-2.93	13.65	-5.04	0.49	-0.18	0.44	-0.16
GrRf+AdBl	4.89	-5.99	8.40	-10.29	0.30	-0.37	0.27	-0.34
GrRf+AdBl+AdWind	4.30	-6.58	7.38	-11.31	0.26	-0.40	0.24	-0.37

(b)

Table 25: Consumptions and reductions in AC use during (a) Present (b) Mid Future TMY

Looking at the tables above, it is noticeable how bigger demands and costs are attested in the Mid Future scenario. This is caused by the more severe conditions that require a high amount of energy for guarantee determined conditions inside the building, with the relative increment of primary energy demand, emissions and costs. Also in this scenario, the highest absolute reductions in all the indicators are present. This highlights the effectiveness, but also the necessity, of passive measure to achieve acceptable sustainability and costs in future climatic conditions. On the other hand, highest emissions values are in the Present scenario. This is caused by the wider use of no-renewable sources, that usually have larger emissions caused by combustion phenomena. Reduction of demand, thanks to passive measures, considerably decreases CO_2 released in the atmosphere, highlighting the necessity of improving energy efficiency in buildings for fighting climate changes, especially in contexts where fossil fuels are widely used.

Relative reductions of consumptions respect to the case without passive measures are shown in Figure 54.

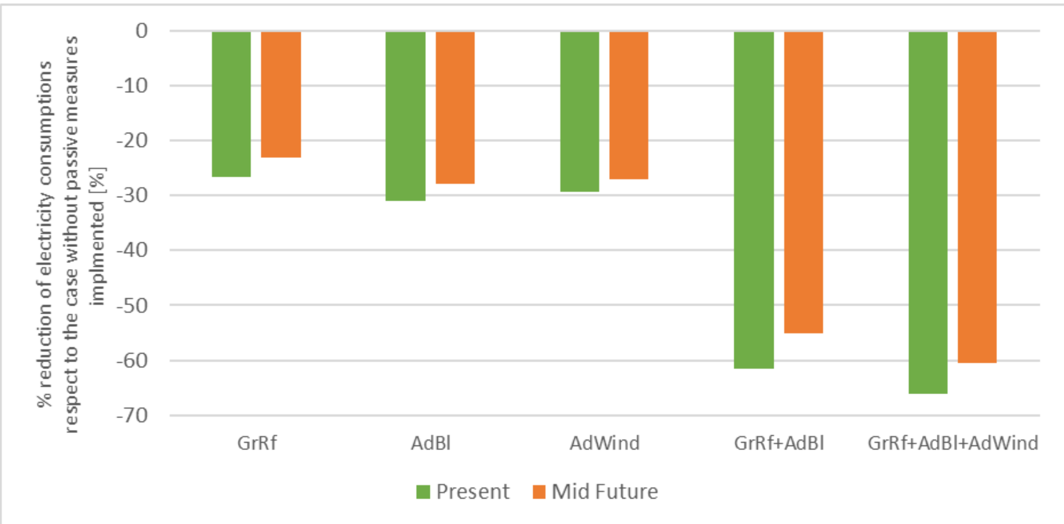


Figure 54: Relative reductions of AC electricity consumptions respect to the case without passive measures during Present, Mid Future and Long Future TMY

Best performances among the different technologies are achieved in the Present scenario. This is explained by the worse outdoor conditions in the future years, that impose the intensive and continuative use of active measures also in case of passive technologies installed. Among the different technologies, advanced solar shading is the one that achieved the best results alone, reducing demand by 31% and 28% in the two scenarios. Combinations of two or three measures can reduce considerably vapor compression refrigeration consumption, arriving respectively to 61% and 66% of reduction in the Present year, confirming the effectiveness of these choices. It is important to notice how reductions are lower than the ones obtained in free running and under natural ventilative cooling regime. This is mainly caused by average better conditions inside the building during summer, thanks to the active measure implemented, that also requires less cooling energy for maintaining them.

6.2.3. Reductions during HWs

The same analysis is conducted for heatwave periods. Absolute and relative savings achieved with the use of the different passive technologies installed are shown, respectively, in Table 26 and Figure 55.

Present Most Severe HW								
Passive Technology Implemented	Electricity Comsumption [kWh/m^2]		Primary Energy Demand [kWh/m^2]		CO2 emissions [kg-eq/m^2]		Costs [€/m^2]	
	Total	Reduction	Total	Reduction	Total	Reduction	Total	Reduction
None	1.053	0.000	2.494	0.000	0.349	0.000	0.070	0.000
GrRf	0.871	-0.182	2.063	-0.431	0.288	-0.060	0.058	-0.012
AdBl	0.882	-0.171	2.088	-0.406	0.292	-0.057	0.059	-0.011
AdWind	0.850	-0.204	2.012	-0.482	0.281	-0.067	0.057	-0.014
GrRf+AdBl	0.661	-0.393	1.564	-0.930	0.219	-0.130	0.044	-0.026
GrRf+AdBl+AdWind	0.586	-0.468	1.387	-1.108	0.194	-0.155	0.039	-0.031

(a)

Mid Future Most Intense and Severe HW								
Passive Technology Implemented	Electricity Comsumption [kWh/m^2]		Primary Energy Demand [kWh/m^2]		CO2 emissions [kg-eq/m^2]		Costs [€/m^2]	
	Total	Reduction	Total	Reduction	Total	Reduction	Total	Reduction
None	1.678	0.000	2.885	0.000	0.103	0.000	0.098	0.000
GrRf	1.448	-0.230	2.489	-0.396	0.089	-0.014	0.084	-0.013
AdBl	1.275	-0.403	2.191	-0.694	0.078	-0.025	0.074	-0.023
AdWind	1.369	-0.309	2.354	-0.531	0.084	-0.019	0.080	-0.018
GrRf+AdBl	0.998	-0.680	1.716	-1.169	0.061	-0.042	0.058	-0.040
GrRf+AdBl+AdWind	0.893	-0.786	1.534	-1.350	0.055	-0.048	0.052	-0.046

(b)

Table 26: Consumptions and reductions in AC use during (a) Present Most Severe (b) Mid Future Most Intense and Severe HW

In case of heatwaves, demands, emissions and reductions depend both on the time period, having different scenarios in electric generation, and on the characteristics of the event. In fact, like for TMY, largest emissions are present in the closer scenario, for the lower share of renewable systems in electric production. Whereas, the highest electricity consumptions, primary energy demands and costs are on the Mid Future heatwave. This is caused by the local highest temperatures during the period and probably by a less effective vapor compression refrigeration system, not prepared for this extreme event because of its big difference from the typical weather.

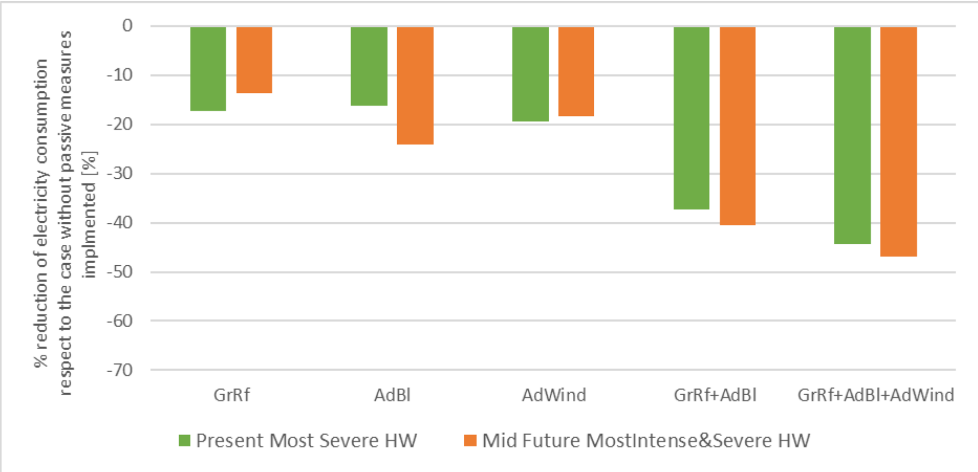


Figure 55: Relative reductions of AC electricity consumptions respect to the case without passive measures during Present Most Severe and Mid Future Most Intense and Severe HWs

Regarding percentual variation respect to the Base Case, single technologies modify their performances basing mostly on the characteristic of the event, rather than on the time period. For example, green roof has better performances in the earlier scenario, while advanced solar shading achieves best results in the latter one. Advanced glazing maintains a similar relative reduction along all the scenarios. Also in this case, the best performances are achieved by the combinations of all measures, reducing consumptions up to 44%, 47% during Present and Mid Future. It is important to confront the results of HWs analysis with the one of TMY. In fact, reductions of AC energy demand are higher in case of typical year rather than during heatwaves. This effect can be related to the worst conditions during the extreme periods, that do not permit the system to relax, requiring a larger amount of electricity and for more continuous hours.

7. Conclusions

In this work the effects of new climatic conditions and extreme events on the most typical Catalan residential building and the improvements provided by different cooling techniques have been analyzed. The aim was to provide a preliminary analysis for determining possible configurations of the building, in order to be resilient to future weather conditions, heatwaves and power outages.

Created weather files highlighted the severity of future climatic conditions in case of maintenance of actual levels of GHG emissions. Average annual temperature increment respect to the one of historical scenario resulted equal to 2 °C, 3 °C and 5 °C for Present, Mid Future and Long Future respectively. This led to a significant increase of cooling degree days and reduction of heating ones in the future, with the consequent modification of the duration of cooling and heating seasons. Future heatwaves resulted longer and more severe respect to the actual ones, increasing overheating risk inside the dwellings.

Testing the created weather scenarios on the original building, the modification on annual thermal energy needs caused by climate changes was pointed out. Needs resulted reversed respect to the one obtained in historical weather conditions, being cooling needs higher than heating ones, especially in the latter scenarios. This aspect was also found in the amount of hot and cold discomfort hours during the year, with the first increasing and the second decreasing. During the typical year, the building seemed to be resistant to new weather conditions. It was noted that this parameter was badly affected by progressive more severe outdoor conditions, results of climate change, that increased its value. In fact, the dwelling appeared more resistant in the earlier scenarios rather than in the latter ones. Survivability was guaranteed for the more than half of annual hours, but in the last scenario dangerous conditions had a significant presence during the year, close to 12% of the total occupied hours. Even if resistance and comfort was acceptable during the whole year, operative temperatures inside the building reached high values during summer periods. This phenomenon is particularly serious in the last floor south-exposed apartments, where temperature arrived up to 39.4 °C during Long Future scenario, because of the high surface of exposure to outdoor air and incident solar radiation. In case of heatwaves, similar results were obtained in the resistance assessment, being the building almost prepared for severe outside conditions. Although, compared to typical scenarios, resistance resulted lower, because of the worse climatic conditions. In any case, distinction between TMY and heatwave scenarios were not very significant. On the other hand, more important differences have been highlighted in the comfort levels. Hours were mainly covered by extremely caution levels of safety in the present, for approximately 60%, while dangerous ones constituted the majority during future scenarios, up to 72% of the total. Operative temperatures have been badly affected by extreme warm conditions, reaching the value of 41 °C in the most exposed apartments. From these last considerations, it was possible to say that, despite acceptable results for resilience indicators, the building was not prepared for facing new climatic conditions and heatwaves. Reasons could be related to inadequate construction characteristics and absence of preventive and protective measures.

Implementing different cooling techniques, results during TMY were significantly improved. Good results were achieved for climate resistance by all the technologies. Installation of exclusively Category A measures improved it, but their contribution was less effective than the one obtained by natural ventilative cooling and vapor compression refrigeration. These aspects highlighted the importance of higher ventilation rates during the hot periods of the year, that ensure protection from overheating risk. Although, it should be mentioned that natural ventilative cooling faced less effectiveness during the future scenarios. Hours of hot discomfort were reduced by all the technologies, with their contribution dependent on their proper characteristics. On the other hand, cold discomfort was not significantly modified or it was even increased by these cooling measures. Survivability was ensured by all cooling technologies in the Present scenario and most of them in the Mid Future one. During Long Future TMY, only vapor compression refrigeration could avoid dangerous conditions inside the building.

In case of heatwaves, cooling technologies performances were strictly dependent on outside conditions. In fact, passive measures achieved important improvements of climate resistance in the less severe scenarios. Combinations of passive measures obtained good results in the Present, but their performances decreased in Mid and Long future. Natural ventilative cooling suffered even worse losses of efficiency moving through the years. At the meantime, vapor compression refrigeration maintained excellent levels of resistance in all the scenarios. Discomfort hours were reduced by all the technologies, but only natural ventilative cooling and combinations of Category A measures were able to avoid them in all the Present and Mid Future heatwaves. During Long Future ones, passive measures could not cancel hours characterized by hot discomfort. Vapor compression refrigeration reduced discomfort hours, performing the best reductions in the configuration with only advanced solar shading applied. Survivability was always guaranteed in the present years, but presence of dangerous conditions was significant for most configurations during the future ones. These results highlighted the necessity of these Category B measures in case of heatwave. All the technologies reduced indoor operative temperature, but no one was able to maintain it under 26 °C, reference value for calculation of indoor overheating. This remarked the difficulties of the building in resisting extreme weather events, suggesting the reduction of setpoint temperatures of mechanical cooling systems during their occurrence.

During the events of power outages, passive technologies were necessary measures for improving conditions inside the building, in absence of vapor compression refrigeration. For all the scenarios, the building obtained results of climate resistance that were better respect to the ones evaluated for the same heatwave in buildings without mechanical conditioning systems. Green roof was the single measure that achieved the highest reductions of discomfort hours. Regarding thermal survivability, it was slightly improved respect to the buildings without active measures, but dangerous conditions were difficulty avoided during future heatwaves. Significative differences between the technologies were achieved in the reduction of operative temperature during outage hours. Green roof and its combination with advanced solar shading and advanced glazing could maintain low values, especially during long outages, and helped considerably in the restoration of comfort conditions after the disrupting event.

Results of climate resistance assessment highlighted the adequacy of building and cooling technologies in maintaining acceptable indoor overheating degrees in relation to warmness of outdoor space. In contrast, discomfort hours and thermal survivability suggested that the dwelling is not always prepared for disrupting events and requires several cooling technologies for maintaining comfortable or acceptable conditions inside it. In this view, it is important to visualize which techniques or combinations of them can make the building resilient to the different events. Combination of Category A measures with natural ventilative cooling, as well as vapor compression refrigeration can be defined resilient to new average climate conditions. During heatwaves, this property can be assigned to vapor compression refrigeration for all the time periods, while this is true only for Present scenario when passive techniques are implemented. In case of power outages, the building can be considered resilient to this kind of event only when the combination of minimum three passive measures is applied.

At the end, impact of each technology on thermal needs and electricity consumptions of building was evaluated. All the techniques, alone and combined, reduced cooling and total needs, whereas some of them increase the heating one. The only measure that impacted positively on all three needs was green roof, while advanced glazing obtained the same, with less effectiveness, only for Present and Mid Future. Natural ventilative cooling was the single technology that provided the best reductions on cooling need. Although, in the future scenarios, its effectiveness was significantly reduced. Combination of all the Category A techniques and ventilation was the best configuration for decreasing cooling and total needs in all the scenarios. Passive measures impacted significantly also on the electricity consumption of vapor compression refrigeration during TMY and HWs. Although, their contribution was less important than the one provided on the thermal demand, because of better average indoor conditions maintained by the active measure during the investigated periods. Significative reductions have been calculated for primary energy need, carbon emissions and costs. Despite major absolute reductions during Mid Future, the highest relative reductions compared to the case without passive technologies were achieved in the Present. This is explained by the severe climatic conditions of future years, that lead to the frequent use of vapor compression refrigeration, despite the implementation of passive technologies.

8. Limitations and Future work

Despite the result of this work could be considered satisfactory, several aspects limited completeness and variety of the analysis.

The first aspect is related to the concept of resilient cooling for buildings. According to the definition of Attia et al. (105), it is composed of four main parts. In this work, only the first two, vulnerability and resistance, have been deeply evaluated. This was caused by the major complexity of formulation and simulation of the other two steps, robustness and recovery. Although, for a complete comprehension of the phenomenon, all the parts should be investigated, with the use of adequate indicators. In addition, several incongruities in the results were found that resilience assessment. In several scenarios, resilience indicators defined the building as resistant to disrupting events but not able to guarantee comfortable and safe conditions. Other considerations could be made comparing levels of resilience achieved in the different apartments of the building. This would help in the design of differentiated refurbishments for each zone of the building.

The second aspect is connected to the difficulties in setting suitable schedules and parameters for some cooling technologies. For example, measures like advanced solar shading badly affected heating need. This was caused by unsuitable criteria of utilization for some periods of the year, that do not always consider variability of weather in the correct way.

A deeper and optimized analysis may provide solutions for these problems. For this reason, future improvements of this work should focus on:

- Including robustness and recovery steps in the analysis of resilience. This could be done using specific indicators or creating new ones, to provide a complete view of the phenomenon.
- Understanding deeply the concept of resilience and changing or optimizing indicators, in order to obtain congruent and unique results.
- Investigating levels of resilience and comfort of the different zones of the building, proposing specific interventions for each apartment and component.
- Optimizing utilization and parameters of the different cooling techniques. This would solve unpredicted and wrong results of the study. A sensitivity analysis could be the most efficient and effective way for obtaining the best input values.
- Simulating more cooling technologies in the model, to have a wider choice of resilient measures, finding the best combinations to implement.
- Evaluating costs of installation, operation and maintenance of the different cooling techniques, in view of possible real installations.

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