Pre-print

Assessing the effectiveness of green roofs in enhancing the energy and indoor comfort resilience of urban buildings to climate change: methodology proposal and application

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Abstract. The effects of climate change on the built environment represents an important research challenge. Today, green roofs (GRs) represent a viable solution for enhancing energy and urban resilience in the face of climate change, as they can have a positive impact on the building's indoor thermal comfort and energy demand, as well as inducing various environmental benefits (easing urban heat island effects, improving the management of runoff water, reducing air pollution, etc.). Thus, it is important to be able to assess their effectiveness, both today and under future climate conditions, in order to evaluate whether they can also provide a valid long-term solution. In this paper, a simulation approach is proposed to evaluate the energy and indoor-comfort efficacy of GRs installed on a cluster of buildings with respect to climate change and demographic growth. To illustrate the proposed methodology, it has been applied to two European urban environments characterized by very different climatic conditions (Esch-sur-Alzette in Luxembourg and Palermo in Italy) considering their behaviour over a period of 60 years (2020, 2050, 2080). Results showed that, with respect to standard existing roofs (i.e., without the presence of green coverage), and considering the rising temperatures due to climate change, during cooling seasons GRs enabled significant energy savings (ranging from 20% to 50% for Esch-sur-Alzette and from 3% to 15% for Palermo), improvement of the indoor comfort (reduction of the average predicted mean votes – PMVs) and attenuation of the ceiling temperatures (2-5 °C for both contexts) of the buildings' top floors.

Keywords: Green roofs; energy building simulation; indoor thermal comfort; energy savings; climate change adaptation; urban buildings resilience.

1. Introduction

Resilience is defined as *"the ability of an individual, a household, a community, a country or a region to withstand, to adapt, and to quickly recover from stresses and shocks"* [1]. Amongst such stress factors, climate change has become a serious concern worldwide, with implications for health, social security, geopolitical stability (climate refugees), biodiversity safeguards and infrastructure protection. In the urban context, one of the most evident negative effects of climate change certainly consists of the increasing tendency to affect the energy and environmental performance of buildings, thus triggering concerns about building sustainability and occupant comfort [2,3].

Energy demand in the building sector is responsible for 36% of energy use worldwide (corresponding to 39% of total energy-related CO_2 emissions) [2, 3], while at the European level, the building sector accounts for a 25-40% share of total energy demand (corresponding to about 35% of the overall CO_2 emissions throughout Europe) [4, 5]. These figures (i.e., the percentage values related to building energy demand, especially residential buildings) will most likely increase considering recent events (Covid-19 pandemic) that led a large number of people to spend much more time inside their dwellings. This has, in turn, highlighted even more the utmost importance of paying adequate attention to maintaining optimal indoor comfort conditions, while still consuming less energy.

Therefore, adaptation strategies supported by relevant technical solutions and legislative strategies are of paramount importance to make cities more sustainable and resilient [8–10].

At the global level, city sustainability is one of the key aspects of the Sustainable Development Goals – SDGs (precisely Goal 11, 12 and 13) [11], aiming to make cities more inclusive, resilient, competitive and resource-efficient, and to mitigate and adapt to climate change. The EU has long been involved in implementing policies aimed at promoting a more sustainable and resilient society, e.g. with the 2020 "climate and energy package" [12], 2030 "climate and energy framework" [13] and 2050 "long-term strategy" [12, 13]. Accordingly, some standards and regulations have been issued specifically for the building sector, namely the EPBD Directive and its recast [16–18], stating that new buildings (built from 2021 ahead) have to be nearly zero-energy (NZE) buildings.

New concepts, such as "regenerative sustainability" [19], have now also entered in the common lexicon of the international research community [20–23], with the aim of fostering energy and environmental-adaptive approaches [24]. One of the merits of regenerative sustainability in the building sector is the consolidation and promotion of the perception of buildings as more dynamic and interactive structures [25]. Under this conceptual paradigm, a large spectrum of technical solutions for the building envelope are fostered to ameliorate the occupants' perception of indoor and outdoor space, improving not only their comfort, but their whole general well-being. These are known as bio-inspired, bio-based or nature-based solutions, like green (or vegetated) façades, green walls and green roofs (GRs). The latter, in particular, have proven effective in mitigating the effects of extreme weather events like heatwaves [26] or heavy water runoffs [27], and phenomena like urban heat islands (UHIs) [28–30]. They are also considered beneficial for the whole urban ecosystem with respect to functions like air purification, with a consequent reduction of air pollution, mitigating noise and increasing biodiversity [31–33]. Furthermore, as claimed in previous studies, GRs also have a beneficial effect in terms of water runoff reduction, acting on both (although limitedly) water filtration and on flooding limitation [32, 33]. This positive effect of GRs is particularly important in view of the increasingly frequent heavy rainfall events causing large-scale flooding, like the severe flood that hit the city of Palermo on 15 July 2020 [36].

The effects of green (or vegetated) roofs on buildings have been studied by several authors considering various aspects, such as indoor microclimatic conditions, energy performance, reduction of carbon emissions and LCA, and have shown a rapid increase in recent years [35, 36]. In particular, the effects on a building's indoor thermal conditions and energy performance due to the presence of GR have been extensively discussed in the literature (with one of the first studies on the subject dating back to twenty years ago [39]).

From the thermal point of view, the first effect of vegetated roofs consists of a reduction in the heat transfer to the building [38, 39], consequently improving the indoor comfort conditions (in some cases up to the second-to-last floor), mostly by attenuating the ceiling temperatures [42,43].

An improvement in the indoor conditions, in turn, also has an impact on the building's energy behaviour, the extent of which depends on the climatic context considered [44]. Several studies have indeed demonstrated a correlation between thermal comfort – mainly estimated using indoor air temperature and predicted mean vote (PMV) values – and energy performance, concerning heating and cooling loads [45,46] and/or air conditioning installed power [45, 46].

Other studies have underlined that aspects that need to be adequately considered during the GR design phase are those regarding the link between the achievable energy savings and the plants species growing on the roof [49] and those concerning the impact that the selected substrate has on the thermal [50–52], environmental [53,54] and energy [53, 54] performance of GRs. A few relevant parameters concerning the energy modelling of GRs have also been investigated, specifically referring to the role played by plant species and solar radiation in the thermal exchanges between the vegetated layers and the surrounding environment [57–59].

Moreover, the influence of vegetated roofs on heat transfer has been simulated not only with reference to their purely vegetative characteristics (plant species, foliage coverage, evapotranspiration, etc.) [60], but also in combination with other building components or technical solutions, such as innovative roof insulation components [61], ventilation [62] window shadings [37] and photovoltaic systems [63,64].

Concerning the energy aspect, the effects of GRs on heating and cooling loads have also been examined in relation to the UHI mitigation potential, with them being able to lower the outdoor temperatures in their proximity under different climatic contexts [2].

From an environmental standpoint, various analyses have been carried out by means of the LCA methodology, going from the single impacts of the layers used in the construction of GRs [65], to a more comprehensive evaluation [63, 64], including a comparison with traditional standard roofs [68].

Some papers have also highlighted as a benefit the reduction of direct and indirect carbon emissions related to buildings' air-conditioning that can be obtained with such an envelope component [41, 56].

Concerning the economic aspects, previous studies [66, 67] performed at the single building level have demonstrated that, although GRs are often not a cost-effective solution on private single houses, they become economically more competitive on a larger scale, especially when aesthetic and social benefits (such as UHI attenuation, greenhouse gases emissions and storm-water runoff reduction) are also taken into account.

In light of the given framework, it is apparent how, on the single building level, the capability of GRs to reduce energy needs for the climatization of buildings, their positive effects on indoor thermal conditions and their environmental benefits have been extensively investigated in the literature, while at a scale larger than that of the single building, there are very few studies to date [71].

With the aim of contributing to filling this gap, this paper explores the environmental effects of a possible extension of the GRs' positive influence on a wider urban scale, an aspect often overlooked in the estimation of the performance of these passive building envelope components. In this perspective, it is of extreme importance not only to be able to quantify and assess the extent to which these solutions can be effective in improving the climate resilience of buildings today, but also of being capable of forecasting this effect under future climate scenarios.

This paper investigates these aspects. To this end, the study quantifies the effects of GRs on the energy loads and indoor comfort of the top floor of the buildings in which they are installed, both in today's climate conditions and under future socioeconomic and climate scenarios (2050 and 2080 projections). For the sake of completeness, it must be reiterated that the effect on indoor comfort is not the only effect on comfort caused by GRs. In fact, they also contribute to the mitigation of the UHI effect and the consequent improvement of outdoor comfort conditions. As the literature has proven, this effect depends significantly on the climatic zone and level of dryness of the GR, with the greatest mitigation being reached in the evenings and the lowest on cloudy winter days [2]. However, while at the rooftop level the temperature mitigation can still be appreciated, the mitigating effect on UHI at the pedestrian level is negligible in all climates [2]. In this case, other greening interventions, such as the introduction of trees and urban vegetation at the street level, are a more effective mitigation strategy [72], possibly coupled with a city-wide (as opposed to scattered) deployment of GRs [73]. However, the scope of this paper is limited to the investigation of the effects of GRs on the indoor building environment, therefore it does not take into account mitigation effects of GRs on UHI. The cases of two European cities characterized by very different climate classifications were considered: Palermo, in southern Italy and Esch-sur-Alzette, in Luxembourg.

2. Materials and methods

The study takes a simulation-based approach based on the methodology flowchart showed in Figure 1, where the thermal building simulations and their outcomes are framed by thick red boxes.

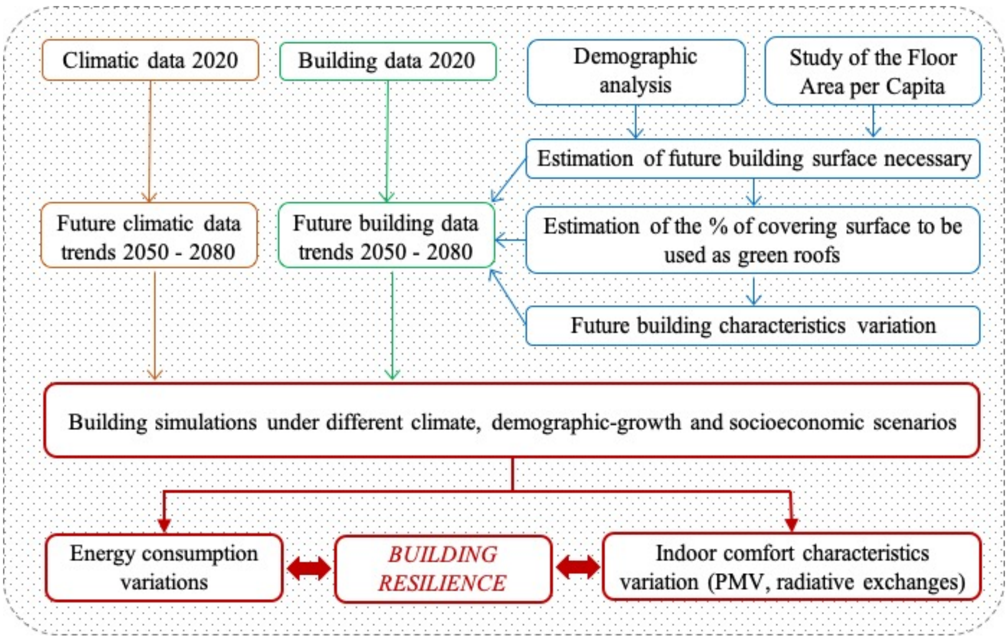

Figure 1. *Block diagram showing the workflow adopted in the paper.*

As shown in Figure 1, "Future building characteristics variations" were considered, including glazed surfaces, which have a relevant influence on the building energy demand [74]. However, the impact of these variations on energy demand was not assessed, since the objective of this work is to analyse exclusively the effect of the GR.

The following sections will describe in detail each step of the block diagram shown in Figure 1.

2.1. Climatic description of the two investigated sites

Concerning the climate characteristics of the two cities studied, Esch-sur-Alzette belongs to the West European Continental climatic region (Cfb – Temperate oceanic climate [69, 70]), while Palermo's weather conditions are typical of a subtropical Mediterranean climate (Csa – Hot-summer Mediterranean climate [69, 70]).

Table 1 summarizes the main weather parameters for the selected cities in order to better highlight the difference between them according to the well-known Köppen-Geiger classification [69, 70], and also to point out their diverse climate characteristics during the heating and cooling seasons. These have been extrapolated from the weather database of the EnergyPlus simulation code[1], which was used in this work.

Table 1. *Main weather parameters for the two selected cities.*

	Esch-sur-Alzette (Luxembourg)	**Palermo (Italy)**
Latitude	49°29′49″ N	38°06′56.37″ N
Longitude	5°58′49″ E	13°21′40.54″ E
Altitude in meters (a.s.l.)	352	14
Köppen-Geiger climate class	Cfb	Csa
Heating Degree Days (HDD) [a]	2773	1000
Cooling Degree Days (CDD) [b]	11	73
Cumulate solar radiation for heating season (MWh) [a]	281	526
Cumulate solar radiation for cooling season (MWh) [b]	808	1156

[a] Considering heating season period 15th October – 14th April [87, 77].

[b] Considering cooling season period 15th April – 14th October [87, 77].

2.2. Climate analysis and weather scenarios trends (2020, 2050, 2080)

As mentioned above, the weather data used for simulations for Palermo were obtained from the EnergyPlus website database[2], while for Esch-sur-Alzette, the weather data file for Luxembourg, retrieved from the Climate.onebuilding website[3], was used.

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[1] https://energyplus.net (Accessed on 10th July 2020)

[2] https://energyplus.net/weather (Accessed on 10th July 2020)

[3] http://www.climate.onebuilding.org/WMO_Region_6_Europe/LUX_Luxembourg/index.html (Accessed on 10th July 2020)

The weather files related to the three future years considered, 2020, 2050 and 2080, were built using the Climate Change World Weather Generation (CCWorldWeatherGen) tool [78]. This tool allows us to obtain a future hourly weather file starting from an existing one using the IPCC TAR model summary data of the HadCM3 A2 experiment ensemble (HRM3). In particular, the tool was built using the time series adjustment (morphing) technique as a statistical downscaling method to develop a future weather file based on an existing .epw file [78–80]. In fact, building simulation models (such as EnergyPlus) require hourly data as their input while Global Climate Models (GCMs) provide only large spatial scale monthly data, which hence need to be temporally and spatially downscaled. The weather file for 2020 was also generated using this tool, in order to have an equal refence point, since the .epw files related to the climatic data of the two considered sites refer to different years of origin. Figure 2 shows the annual trend of outdoor air temperature and solar radiation for 2020 for Luxembourg and Palermo, obtained from the data contained into the .epw files generated by CCWorldWeatherGen tool.

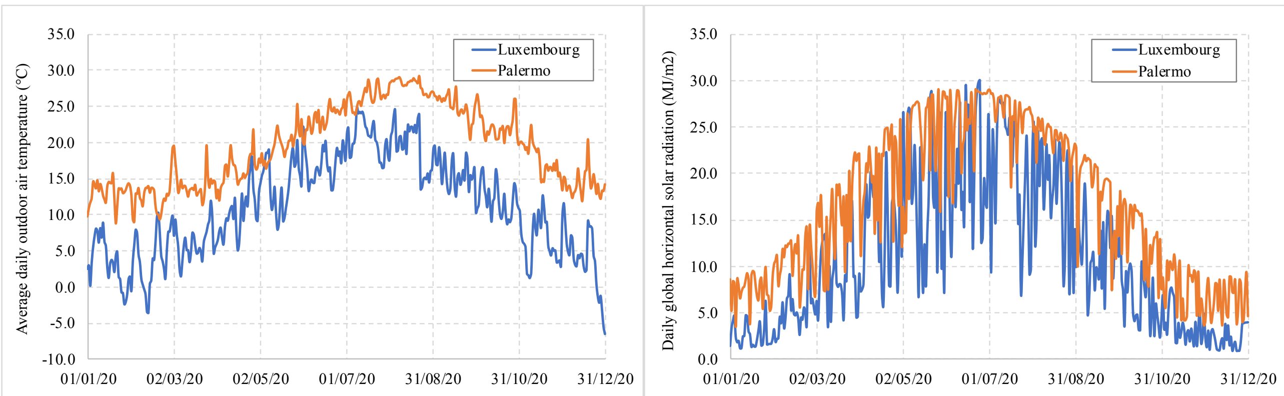

Figure 2. *Trends of outdoor air temperature (on the left) and annual solar radiation (on the right) for Luxembourg and Palermo, for the year 2020.*

It should be noted that the authors chose to utilize the SRES A2 model as its structure better approaches a Business as usual (BaU) scenario. In fact, although the more recently released RCP 8.5 is based on and close in character to the SRES A2, it is unlikely to be used as a BaU scenario [81], as for the middle of the century, it is much more pessimistic than the A2 [82].

2.3. Analysis of the evolution of built surfaces: 2020-2050-2080 trend

The evolution of the built surface for the future scenarios in the two areas studied was estimated using the current building and demographic data, taken from the websites of the national statistics offices respectively of Italy (www.istat.it) and Luxembourg (www.statec.lu), as a reference. They were analysed and combined with the information related to the floor area per capita [83,84] in order to calculate the future building floor surface and the building footprint areas required and, hence, estimate the future area available for the GRs. These aspects will be further detailed in Sections 2.3.1 and 2.3.2.

Regarding the future scenarios, we decided to refer to the Shared-Socioeconomic Pathway (SSPs) assumptions, introduced in [85,86]. The rationale behind the SSPs is that the socioeconomic conditions and drivers with a significant impact on the energy system and its future growth (such as demographics, economy, lifestyle, policies, institutions, technology and environment and natural resources) can be structured into five alternative development pathways narratives at the level of large world regions. Specifically, the five SSPs are:

- SSP1 *"Sustainability—Taking the green road"*, low challenges to both mitigation and adaptation;
- SSP2 *"Middle of the road",* moderate challenges to mitigation and adaptation;
- SSP3 *"Regional rivalry—A rocky road"*, high challenges to both mitigation and adaptation;
- SSP4 *"Inequality—A road divided"*, low challenges to mitigation and high challenges to adaptation;
- SSP5 *"Fossil-fuelled development—Taking the highway"*, high challenges to mitigation and low challenges to adaptation.

In this paper, we have set out and briefly described all the expected SSP scenarios. Of these, those that are most in line with the purpose of this paper, and with the selected climate scenario (Section 2.2), are SSP1 and SSP2.

2.3.1. Demographic trend study

The demographic trend study was carried out using the population evolution over a 2010-2020 time-window as reference data. Concerning the 2030-2080 period, starting with the comparison between the local (Esch-sur-Alzette and Palermo) and national (Luxembourg and Italy) population data, the ratios (percentages) between the populations of the two cities and the respective national populations were calculated and then extrapolated to the years 2010-2020 using a linear regression. Afterwards, these values were multiplied by the population estimates provided for the respective countries by considering both the future demographic forecasts of the International Institute for Applied Systems Analysis – IIASA[4] and the previously described SSPs [83] to obtain the city populations.

[4] https://iiasa.ac.at (Accessed on 11th August 2020)

Figure 3 shows the resulting projections of demographic trend previsions on a national and local basis, respectively.

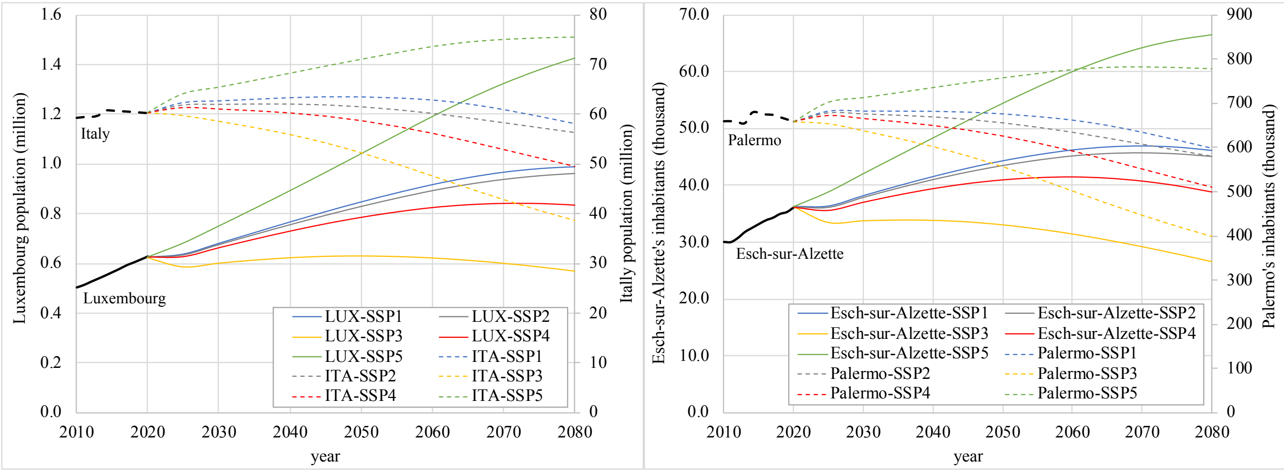

Figure 3. *National demographic trends for Luxembourg and Italy (on the left) and demographic trends for Esch-sur-Alzette and Palermo (on the right), in the five SSPs.*

With Palermo being a large city, shown by the reference data on population growth retrieved from the national statistics office, and taking into account the existing space constraints and the limits (in terms of allowed building areas) imposed by the city building master plan and the redevelopment policies concerning Palermo's southern waterfront zone[5], we deduced that the "Bandita" district considered in this study was one of the most likely to host the future increase in the number of buildings due to demographic growth.

2.3.2. Development of built surfaces

Starting from the results of the demographic trend analysis, the current built-up area data [87–90], and the forecasts of future net floor area per person ($FApC$) [75, 82], it was possible to estimate the future building net footprint area (A_{net}) necessary to accommodate the future population, for the two future time scenarios considered, i.e. 2050 and 2080.

More specifically, for both sites and for all the SSPs, the difference between the expected and current population was first calculated. The result was then multiplied by an $FApC$ value of 45 m^2 to obtain the total building surface (S_{tot}) required in the future to meet demographic growth. The variation in the number of future buildings in terms of the gross footprint area (A_{gross}) was calculated firstly by dividing S_{tot} by 180 m^2, representing the surface area of two standard European apartments (90 m^2 each) [84], and secondly by dividing

[5] https://www.comune.palermo.it/territorio.php (Accessed on 11th August 2020)

this value by the number of floors, thus obtaining the number of standard residential buildings with two apartments per floor. To this end, it was decided to consider 6 and 5 floors as representative values for Esch-sur-Alzette and Palermo, respectively, since, based on data from preceding studies performed by the authors in the two areas, they correspond to the most recent constructed typology of buildings (as reported in the Table 4 below and Table 5 in Section 2.4). Finally, to consider the space occupied by cornices, technical systems and ancillary services for the GRs, A_{net} was estimated considering reduction factors of 12% for Palermo [92] and 20% for Esch-sur-Alzette [87].

Table 2 summarizes the results of the procedure described above applied to Esch-sur-Alzette and Palermo's Bandita district for each of the five SSP and for the three years 2020, 2050 and 2080.

Table 2. *Demographic trend results.*

	Expected population (thousands of people)			Expected population variation (thousands of people)	
	2020	2050	2080	2050-2020	2080-2020
Esch-sur-Alzette-SSP1	36.22	44.30	46.15	8.08	9.93
Esch-sur-Alzette-SSP2	36.22	43.41	45.00	7.19	8.78
Esch-sur-Alzette-SSP3	36.22	33.05	26.64	-	-
Esch-sur-Alzette-SSP4	36.22	40.99	38.88	4.77	2.66
Esch-sur-Alzette-SSP5	36.22	54.42	66.51	18.20	30.29
PA-Bandita-District-SSP1	49.48	50.89	44.98	1.42	-
PA-Bandita-District-SSP2	49.48	49.26	43.64	-	-
PA-Bandita-District-SSP3	49.48	41.84	29.93	-	-
PA-Bandita-District-SSP4	49.48	47.02	38.38	-	-
PA-Bandita-District-SSP5	49.48	56.90	58.43	7.42	8.95

Table 3. *Development of total built surfaces results.*

	Expected number of standard residential buildings		A_{gross} (m^2)		A_{net} (m^2)	
	2050	2080	2050	2080	2050	2080
Esch-sur-Alzette-SSP1	168.29	206.89	3.64E+05	4.47E+05	2.91E+05	3.58E+05
Esch-sur-Alzette-SSP2	149.81	182.89	3.24E+05	3.95E+05	2.59E+05	3.16E+05
Esch-sur-Alzette-SSP3	-	-	-	-	-	-
Esch-sur-Alzette-SSP4	99.35	55.52	2.15E+05	1.20E+05	1.72E+05	9.59E+04
Esch-sur-Alzette-SSP5	379.12	631.05	8.19E+05	1.36E+06	6.55E+05	1.09E+06
PA-Bandita-District-SSP1	470.65	-	8.47E+05	-	7.46E+05	-2.37E+06
PA-Bandita-District-SSP2	-	-	-	-	-	-

PA-Bandita-District-SSP3	-	-	-	-	-	-
PA-Bandita-District-SSP4	-	-	-	-	-	-
PA-Bandita-District-SSP5	2467.43	2976.78	4.44E+06	5.36E+06	3.91E+06	4.72E+06

As can be observed, while Esch-sur-Alzette shows a positive trend for all SSPs except SSP3, the same cannot be said for the Bandita district of Palermo, where only SSP5 and SSP1 show an increase by 2050. The hyphens shown in Table 2 indicate that the predicted negative trends were obtained, which have been considered as no variations.

2.4. Building selection and characteristics

Given the high variety of building types present in both territories considered, it was necessary to select those that were most representative for each site in order to implement simulations that would best reflect reality. To this end, data related to the buildings' geometry and materials, and the layout of the studied city areas were retrieved from previous projects and monitoring campaigns realized by the authors in the respective areas [87–90] and were loaded on a Geographic Information System (GIS) platform.

The data collected were then analysed in order to first categorize the existing buildings, based on the construction period, the roof typology (only flat roofs were considered), the kind of materials utilized for both the opaque and glazed surfaces, and the technical installations.

Based on the aforementioned categorization, for each town we then decided to select two representative buildings for every construction period to assess the diverse impact that GRs may have on the distinct (real) building configurations. This resulted in a total of eight buildings for each town.

Table 4 and Table 5 report the main geometrical characteristics of the buildings selected in Esch-sur-Alzette and Palermo, respectively.

Table 4. *Geometrical characteristics for the selected buildings in Esch-sur-Alzette.*

Construction period	Building ID	Total number of floors	Building footprint (m^2)	Total heated/cooled surface (m^2)	Main façade orientation
< 1949	LU_Esch_I_01	3	178	535	NE
	LU_Esch_I_02	3	112	335	NW
1950-1968	LU_Esch_II_03	3	167	501	NW
	LU_Esch_II_04	3	168	503	NW
1969-1994	LU_Esch_III_05	5	128	641	NE
	LU_Esch_III_06	5	276	1382	NE
> 1995	LU_Esch_IV_07	3	78	233	NW

	LU_Esch_IV_08	6	488	2929	NE

Table 5. *Geometrical characteristics for the selected buildings in Palermo.*

Construction period	Building ID	Total number of floors	Building footprint (m^2)	Total heated/cooled surface (m^2)	Main façade orientation
< 1945	IT_PA_I_01	4	117	468	NW
	IT_PA_I_02	2	49	98	NW
1946-1971	IT_PA_II_03	5	649	3245	NE
	IT_PA_II_04	4	81	324	NW
1972-1991	IT_PA_III_05	8	279	2232	NW
	IT_PA_III_06	10	984	9840	NE
> 1991	IT_PA_III_07	3	216	648	N
	IT_PA_IV_08	5	475	2375	NW

Table A.1, Table A.2, Table A.3.a and Table A.3.b reported in the Appendix summarize the construction features of interest for the selected buildings in the two towns, where the materials of the specific building elements have been classified according to the UNI TR 11552 standard [93].

For the sake of completeness, it should be underlined here that the shapes of the buildings used in the simulations are the real ones, while concerning the other aspects, approximations were made based on the fact that these buildings were chosen as being representative of a group of buildings classified according to the year of construction. Therefore, the simulated buildings are close to the real ones but have been made more consistent with the types and construction materials of their respective construction periods.

2.5. Implementation of the building simulation model

The building's thermal simulations were carried out using the EnergyPlus simulation software. Specifically, the software was used to evaluate the indoor comfort levels, by means of the predicted mean vote (PMV) index [94] (an international widely recognized indicator [95], and the energy demand for heating and cooling demand of the considered buildings. For this purpose, two different scenarios were implemented for each SSP. More specifically:

- Scenario #1 implements a standard case (ST), i.e. it considers the original roof of the building without any green coverage.
- Scenario #2 performs energy building simulation using the GR configuration provided by EnergyPlus (GR), by substituting the outside layer of the roof with a GR (defined as "Material:RoofVegetation" in

EnergyPlus, which is based on the model proposed by Sailor [50]) characterized by the following parameters, where the vegetative specifics are those relative to the *Halimione Portulacoides* plant species [43]:

- height of plant canopy (m): 0.30;
- leaf area index "LAI" (-): 3.8;
- leaf reflectivity (-): 0.21;
- substrate total thickness (m): 0.15;
- thermal conductivity of dry soil ($W \cdot m^{-1} \cdot K^{-1}$): 0.0816;
- density of dry soil ($kg \cdot m^{-3}$): 446;
- specific heat of dry soil ($J \cdot kg^{-1} \cdot K^{-1}$): 1060.

Halimione Portulacoides is a small greyish-green evergreen shrub that is widespread throughout the world. It is an opposite-leaved plant which grows up to 0.75 m, and its leaves are fleshy, glaucous green colour with a linear-lanceolate shape. The species, flat-growing and mainly with small roots, is in leaf all year around and in flower from July to September. Suitable for light (sandy), medium (loamy) and heavy (clay) soils, it can grow in nutritionally poor soils and within in a wide range of pH (acid, neutral, basic-alkaline and saline soils). It can grow in semi-shade (light woodland) or no shade, preferring moist or wet soil, and can tolerate maritime exposure[6]. Therefore, since *Halimione Portulacoides* is very resistant, requiring little maintenance, and reaches 100% coverage in a short time, it is well-suited to being used for green roof applications in various climates [43].

The irrigation schedule related to the EnergyPlus "SmartSchedule" command was used, set at 4 mm/h from 7 am to 9 am in the period 1 June – 30 September and at 2 mm/h for all other time intervals.

In both scenarios, the schedule for an ideal heating ventilation and air conditioning (HVAC) system was implemented (see Appendix), characterized by 21°C and 25°C as the heating and cooling setpoint temperatures, respectively. These average values were derived from simulations previously carried out using the climatic design-days typical of winter and summer conditions for the two investigated areas, on the basis of the UNI 10349-3:2016 [96] and UNI EN 16798-1:2019 [97] standards.

In addition, an estimation of the CO_2 emission reduction was also performed, considering for the cooling energy demand the emission factors for electricity shown in Table 7.

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[6] https://pfaf.org/user/Plant.aspx?LatinName=Halimione+portulacoides (Accessed on 14th June 2021).

These values were derived starting from the electricity mixes given by [98] until 2050 and using the shares of each electricity source in the mix calculated from [98] and the GWP100 emission factors calculated from Ecoinvent v3.5 with the ILCD 2016 impact assessment method [99].

In the case of Esch-sur-Alzette, an additional step was performed, due to the electricity mix in Luxembourg being heavily dependent on the electricity imported from the neighbouring countries (France, Belgium and Germany). Therefore, firstly the shares of electricity imported from each of these three countries, as well as the Luxembourgish national electricity production, obtained from [100] from 2015 to 2019, were linearly interpolated to obtain the shares until 2050 (see Table 6). Then, the shares of electricity imported from each of the three countries were used to calculate a weighted average of the emission factors for electricity in Luxembourg. The values of the emission factors for 2080 were instead simply obtained assuming a maximum improvement of 10% with respect to the values for 2030. The emission factors calculated take into account the emissions from transmission losses (i.e. those occurring between the “electricity supplied” and “electricity consumed” steps in [101]). These additional emissions were calculated from [101], resulting in about 7.2% for Italy and about 1.5% for Luxembourg.

Table 6. *Shares of electricity imported by Luxembourg (LU) from the neighbouring countries (BR, FR, DE) and produced in the national territory.*

Year	Import from BE (%)	Import from FR (%)	Import from DE (%)	LU own production (%)
2020	5.4	19.5	61.7	13.4
2030	5.7	29.5	47.7	17.1
2040	6.0	39.5	33.7	20.8
2050	6.3	49.4	19.7	24.5

Table 7. *Emission factors for electricity (kg CO_2eq/KWh) used for Palermo and Esch-sur-Alzette.*

Year	Palermo	Esch-sur-Alzette
2020	0.48	0.43
2050	0.20	0.19
2080	0.18	0.17

For heating needs, a thermal emission factor equal to 0.275 $kgCO_{2eq}\cdot kWh^{-1}$ (corresponding to 0.076 $kgCO_{2eq}\cdot MJ^{-1}$) [98] was considered. These values are those usually utilized to estimate the energy demand for climatization purposes, by setting Coefficients of Performance (COPs) equal to 3 and 0.9 for cooling and heating seasons, respectively.

3. Results and discussion

3.1. Application of the simulation model to the single building

This section shows the application of the simulation model at the single building level, considering the climatic data of the three years 2020, 2050 and 2080, to estimate the time trend related to the effectiveness of GRs in the two geographical contexts investigated.

In line with the main aim of this work (i.e. assessing the effect of GRs on indoor comfort and building energy demand for HVAC), we decided to show a comparison between standard roof (ST) and GR by reporting the simulation results related to the PMV values (Figure 5), the ceiling temperatures and the heating and cooling energy savings (Figure 6).

For both geographical contexts considered, the behaviour of the buildings belonging to the same categories was very similar. Hence, in order to simplify the visual representation, we decided to report the behaviour of a building belonging to the oldest construction period for both geographical areas in Figures 5 and 6, as it turned out to be the period that best showed the effects related to the presence of the GR. The graphs relative to all 16 analysed buildings are reported in Figures A.1 – A.12 in the Appendix.

As previously mentioned, PMV is an important indoor comfort indicator. For this reason, we chose to compare the monthly PMV average (solid hatched green and black bars) and the relative peak values (white bars with dashed edges) for ST and GR. Figure 5 shows the results for Esch-sur-Alzette (left-hand side) and Palermo (right-hand side). Values of the PMV around zero indicate a neutral thermal feeling, while negative and positive values indicate discomfort due to cold and hot feelings, respectively. The figure shows that the presence of the GR contributes to the reduction of PMV absolute average values, especially of those related to the summer periods. Such differences are more evident for the buildings situated in Palermo where (for almost every construction period; see Appendix), according to the standard currently in force for the design of the indoor environment [101], the presence of the GR contributes to shifting the expected thermal sensation from an acceptable-moderate level (PMV $\geq$ 0.5) to a moderate-normal level (PMV $\leq$ 0.5). A similar behaviour is also noticeable for the buildings in Esch-sur-Alzette belonging to construction periods I and II, while the other building categories do not seem to be influenced by the presence of green coverage. In other words, the presence of the GR in most cases contributes to bringing the top floors of the building towards better comfort conditions. Moreover, Figure 4 shows that, notwithstanding the abovementioned general positive effects, some issues emerge in the transition months (April for Esch-sur-Alzette and November for Palermo), for which the standard roof exhibits slightly better performances than the GR. This effect is probably due to the additional thermal inertia added by the presence of the GR to the building envelope, which may slow down its response to the changes in climatic conditions occurring in these transition periods.

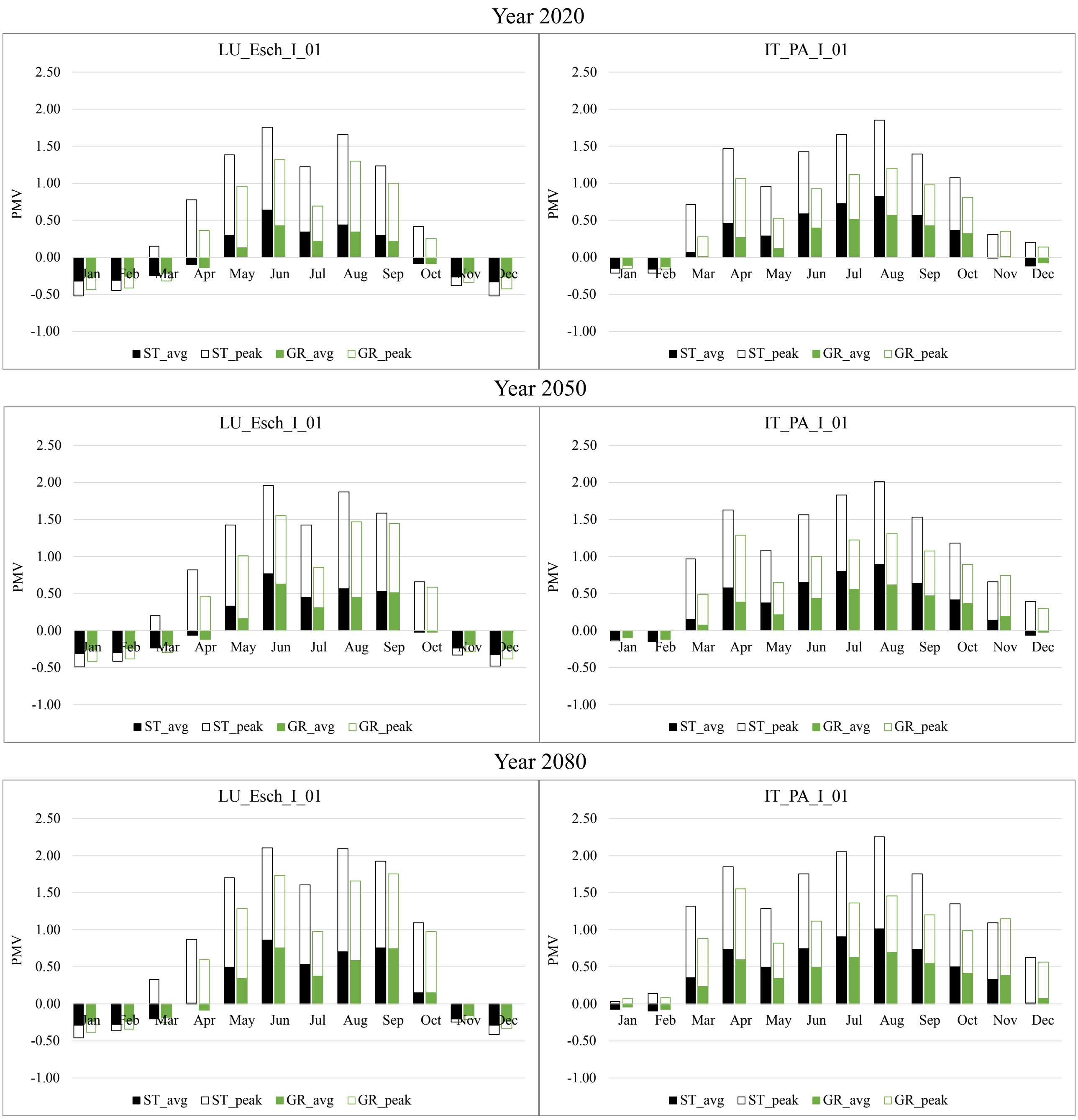

Figure 4. *Comparison between PMV average and peak values in the three years considered (2020 at the top, 2050 in the middle and 2080 at the bottom) for Esch-sur-Alzette (left) and Palermo (right) reference buildings.*

Other than the PMV, another significant parameter when assessing the indoor comfort levels is represented by the ceiling temperature. Figure 5 shows a comparison between the ceiling temperatures of the last floor, with (green line) and without (black line) the presence of the GR. It highlights the positive effects induced by the presence of the GR, which allows ceiling temperatures to be kept higher in winter and lower in summer compared to a standard roof. Specifically, a ceiling temperature attenuation of between 2°C (for Esch-sur-Alzette) and 5°C (for Palermo) can be observed, without significant changes over the years. Once again, such behaviour was particularly noticeable for all construction periods for the Palermo buildings and for buildings belonging to the first two construction periods in Esch-sur-Alzette (see Appendix).

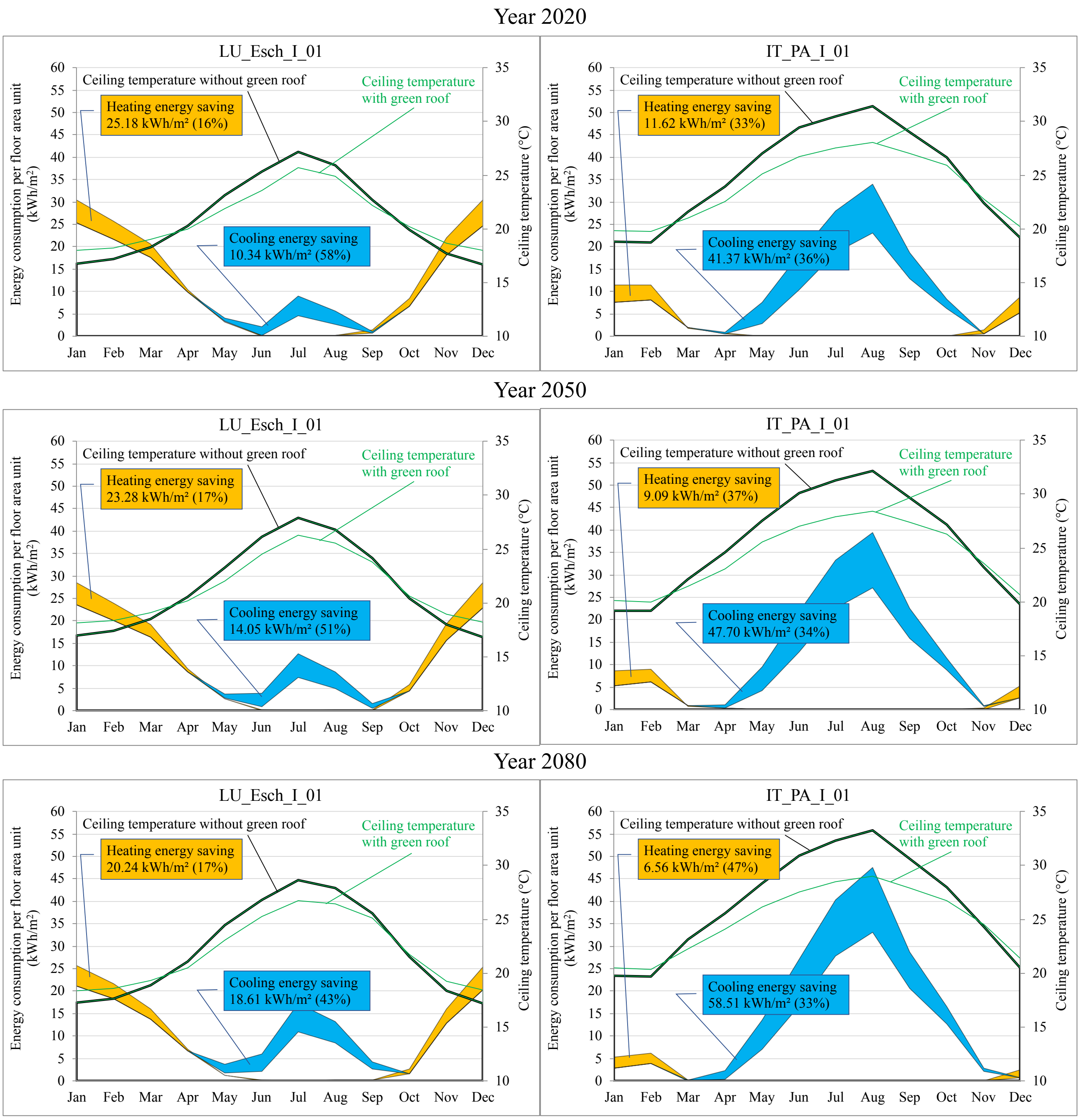

Figure 5. *Comparison between ceiling temperatures and energy savings in the three years considered (2020 at the top, 2050 in the middle and 2080 at the bottom) for reference buildings in Esch-sur-Alzette (left) and Palermo (right).*

As reported in Figure 6, the temperature attenuation induced by the presence of the GR also affected energy demand. In particular, for Esch-sur-Alzette, the energy savings obtainable during summer are greater (~50%) than those related to the winter period (~20%) and are comparable over the years.

As for Palermo, it can be noted that for 2020 and 2050 there is almost no difference between heating and cooling energy savings (3-4% difference), while for 2080, the difference is more accentuated (14% difference), with winter savings greater than summer ones. Once more, similar conclusions can be drawn looking at the outcomes of buildings belonging to all construction periods (see Appendix).

3.2. Extension to the two building stocks considered for the different future scenarios

The simulation model, previously applied at the single building level, was subsequently extended, for each of the SSPs described in Section 2.3, to the current flat roofs fraction (suitable for GR installation) of the building stocks considered in Esch-sur-Alzette and Palermo (Bandita), increased by the future development of the surfaces as described in Section 2.3.2. To this end, we assume that new buildings will have the same constructive characteristics of the surveyed buildings belonging to the most recent construction periods (Table Table **4** and Table 5). In addition, we assumed that between 2050 and 2080, a certain fraction of the existing buildings will be subjected to retrofit interventions; in particular, the retrofit percentages reported in Table 8 were considered (assuming 1% as a worst-case renovation rate [102]).

Table 8. *Building retrofit percentages for Esch-sur-Alzette and Palermo.*

2020	2050		2080		
no retrofit	no retrofit	retrofit_2050	no retrofit	retrofit_2050	retrofit_2080
100%	75%	25%	55%	25%	20%

Moreover, to consider the trend of the technological improvement of the energy performance of the building envelope components, their thermal transmittances (U-values) were upgraded for the new buildings and for the retrofitted ones for 2050 and 2080. These upgrades were assessed, assuming for each component a maximum specific thermal resistance improvement of 1 m^2K/W [103] with respect to their respective best values, and hypothesizing that these maximum improvements take place in the year 2100. Hence, using the thermal transmittance values referring to the building construction year and utilizing a logistic function as an interpolation curve, the new thermal transmittance values for each envelope component have been estimated for 2050 and 2080.

In order to draw conclusions on how the presence of GRs can affect the buildings' energy behaviour in the two very different climatic contexts considered, Table 9 summarizes the comprehensive results obtained for the three years (2020, 2050 and 2080) and the five socioeconomic pathways (SSP1, SSP2, SSP3, SSP4 and SSP5).

Table 9. *Comparison between the energy behaviour of buildings in Esch-sur-Alzette and Palermo (Bandita).*

SSPs	Year	Esch ST Qheat / Qcool (GWh)	Esch GR Qheat / Qcool (GWh)	Esch var % / var %	Palermo ST Qheat / Qcool (GWh)	Palermo GR Qheat / Qcool (GWh)	Palermo var % / var %
-	2020	62 / 8	59 / 7	-5 / -13	18 / 79	15 / 73	-12 / -7
SSP1	2050	84 / 22	82/ 20	-2 / -7	12 / 102	10 / 94	-15 / -7
	2080	72 / 37	72 / 35	-1 / -4	6 / 130	5 / 121	-20 / -6
SSP2	2050	80 / 21	78 / 20	-2 / -7	11 / 94	9 / 88	-15 / -7
	2080	68 / 35	67 / 33	-2 / -5	5 / 120	4 / 113	-20 / -6
SSP3	2050	49 / 13	47 / 12	-4 / -8	11 / 94	9 / 88	-15 / -7
	2080	36 / 20	35 / 19	-2 / -5	5 / 120	4 / 113	-20 / -6
SSP4	2050	70 / 18	68 / 17	-3 / -7	11 / 94	9 / 88	-15 / -7
	2080	53 / 28	52 / 27	-2 / -5	5 / 120	4 / 113	-20 / -6
SSP5	2050	127 / 33	125 / 31	-2 / -6	16 / 132	13 / 121	-16 / -8
	2080	145 / 72	143 / 69	-1 / -4	8 / 179	7 / 165	-22 / -8

Table 9 shows the absolute values of the thermal energy demand at the level of the entire building stock for the two contexts considered: the centre of Esch-sur-Alzette and the Bandita district of Palermo. In particular, the table reports the values for ST, those for GR and a comparison between the two (D%/D%) where D indicates a difference. The data relating to the SSP3, SSP4 and SSP5 scenarios were reported in grey to highlight the fact that they are less related to the paper framework, as previously mentioned in Section 2.3 (this also applies to Table 10 below).

As one could expect, given the climatic zone (latitude) in which the two examined sites are located, higher values for heating were observed for Esch-sur-Alzette, while for Palermo, the greater values are those related to cooling. In fact, the positive trend in energy usage is due to both the increase in population, and therefore in the number of buildings (Table 2 and Table 3), and the change in external climatic conditions. In particular, the rise in temperatures linked to climate change means that the increase in the values referring to heating is less extensive than the corresponding increase for cooling.

Finally, in the last part of this section, an annual estimation of the CO_2 emissions is reported. Table 10 summarizes the data related to the emissions ($kgCO_{2eq}\cdot m^{-2}$) ascribable to the ST roofs and the relative percentages of reduction achievable thanks to the presence of the GR for all the years and SSPs considered.

Table 10. *Annual ST CO_2 emissions and relative savings due to the presence of GR.*

SSPs	Year	Esch-sur-Alzette				Palermo			
		Heating		Cooling		Heating		Cooling	
		ST	GR	ST	GR	ST	GR	ST	GR

		tCO_{2eq}	tCO_{2eq} saving	tCO_{2eq}	tCO_{2eq} saving	tCO_{2eq}	tCO_{2eq} saving	tCO_{2eq}	tCO_{2eq} saving
-	2020	18900	900	1200	200	5400	700	12600	900
SSP1	2050	25600	600	1400	100	3500	500	6800	500
	2080	21900	300	2100	100	1700	400	7800	500
SSP2	2050	24400	600	1300	100	3200	500	6300	400
	2080	20700	300	2000	100	1600	300	7200	400
SSP3	2050	15000	500	800	100	3200	500	6300	400
	2080	11100	200	1100	100	1600	300	7200	400
SSP4	2050	21300	600	1200	100	3200	500	6300	400
	2080	16300	300	1600	100	1600	300	7200	400
SSP5	2050	38800	700	2100	100	4900	800	8800	700
	2080	44100	500	4100	200	2600	600	10700	800

The data reported in Table 10 are intended to simply provide indicative information on CO_2 emission savings for the building sector that could be obtained by implementing this type of intervention.

3.3. Effectiveness of vegetated roofs in enhancing buildings' future climate resilience

The analysis carried out in this work was intended to highlight the effectiveness of GRs as a sustainable building component aimed at improving the resilience of (new and existing) buildings to future climate change conditions, in terms of indoor comfort and energy demand.

Looking at the PMV and ceiling temperature results (Figure 4 and Figure 5), despite a progressive slight worsening of indoor comfort conditions across the years being observed, it can be noted that the GR still allows the effects of future increases in external temperature caused by climate change to be attenuated.

The same considerations can be made with respect to the energy aspect (Figure 5 and Table 9). Although the increasing outdoor temperatures lead to an increase in the cooling loads, the presence of the GR brings an advantage in terms of energy savings, compared to what would be obtained by simply having a standard roof. In particular, from the comparison between PMV peak values, ceiling temperatures and the absolute values of the energy demand (Figure 4, Figure 5 and Table 9), it is evident how the GR technology, in addition to providing an initial advantage in 2020, also allows for future mitigation for the 2050 and 2080 timeframes. Hence, as also shown in Figure 6, this technology seems to represent a valid option to improve the resilience of buildings to global climate change, at least in the climatic zones that have been the object of this study.

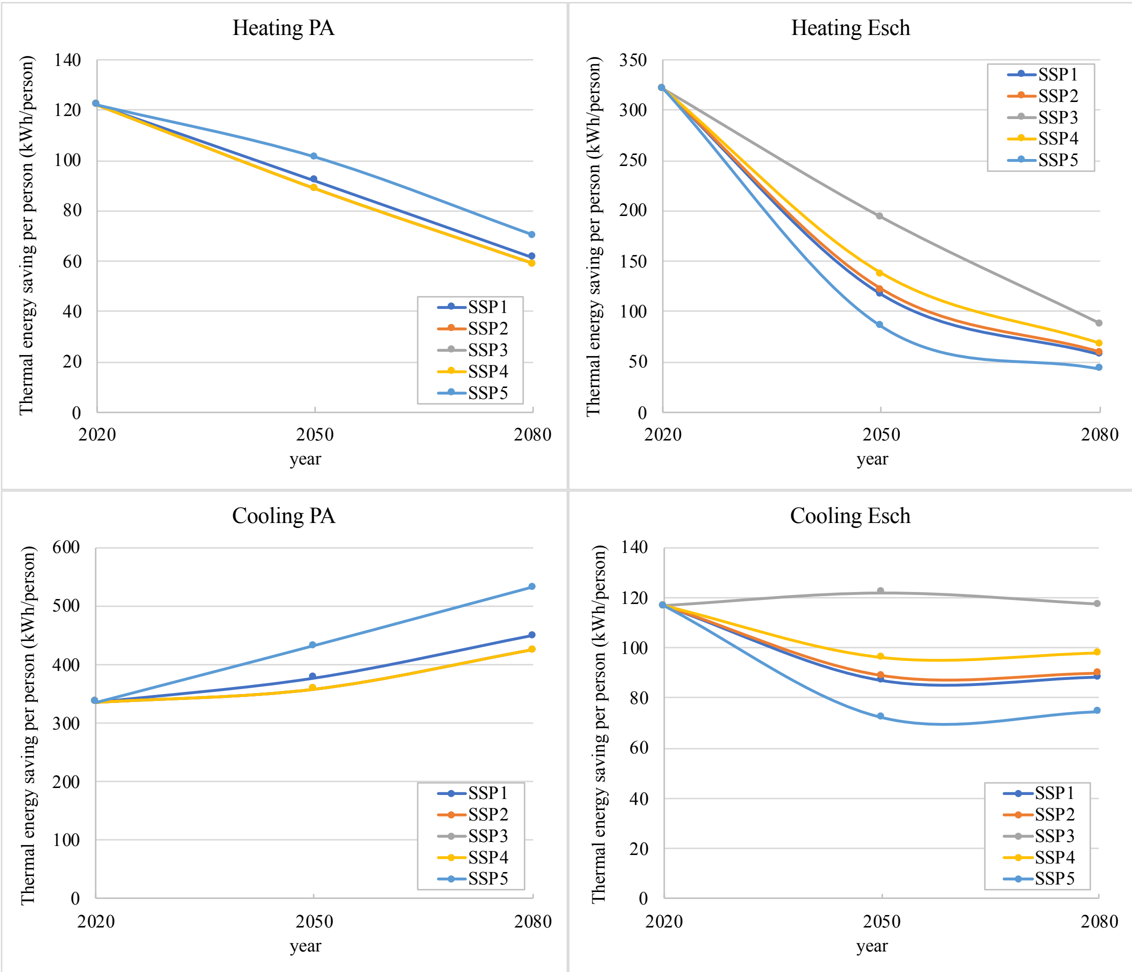

Figure 6. *Comparison between the trends of heating and cooling thermal energy savings per person (2020-2050-2080) in the five SSPs for Palermo (left) and Esch-sur-Alzette (right).*

To give an idea of the order of magnitude of the energy demand, the graphs in Figure 6 show, for the various scenarios considered, the thermal load variations in kWh/person (i.e. the energy consumed per building occupant) related to the presence of the GRs compared to the 2020 standard roof reference values, which are: 6840 kWh/person and 910 kWh/person, respectively, for heating and cooling in Esch-sur-Alzette and 1010 kWh/person and 4510 kWh/person, respectively, for heating and cooling in Palermo.

In order to validate the compliance of the analysis performed, the energy simulations outcomes was compared with the real energy use data related to the residential sector. Specifically, expressing the simulation outcomes in terms of primary energy, for Italy we would find an energy demand for indoor air conditioning of about 0.38 toe/person, corresponding to about 70% of the total energy use. For Luxembourg, the energy demand for indoor air conditioning would be about 0.71 toe/person, corresponding to 85% of total demand. These values are in line with the real energy demand data reported by Eurostat[7], for Italy (67%) and Luxembourg (84%), respectively.

In Figure 6, the lower curves refer to the scenarios for which there is no increase in population and no increase in the number of buildings (see, Table 2 and Table 3), therefore the positive effects are only ascribable to the presence of GRs on existing buildings. On the other hand, when there is an increase in population, and consequently in the number of buildings, the cumulative positive effects are due not only to the presence of GRs, but also to the fact that new buildings inherently function more efficiently than the existing ones (due to improved technology).

Climate change leads to a rise in temperatures, therefore in the future, the beneficial effects due to the presence of the GRs may tend to decrease. In fact, looking at Figure 6 it can be observed that for both sites there is a reduction in heating energy demand, which decreases over the years. The same cannot be said for the reduction in energy demand related to cooling. In fact, while for Palermo such reduction becomes increasingly important across time, for Esch-sur-Alzette an opposite trend can be observed. This circumstance is linked to the influence of the different geographical positions of the two cities on their respective climates, and to the fact that a ameliorative retrofit of buildings over the years has previously been considered (for which the GR has a lower benefit in percentage).

Overall, however, one can say that in the examples we have explored, the presence of the GRs makes the buildings more resilient to the increase of the outdoor temperature.

4. Conclusions

This paper aimed to investigate vegetated roofs used as passive building envelope components in order to improve buildings' resilience to climate change, since they represent a very common solution in recent years. Specifically, the impact of GRs on urban energy and environmental resilience in relation to diverse climatic contexts (Esch-sur-Alzette in Luxemburg and Palermo in Italy), and under future socioeconomic and climate scenarios (2050 and 2080 projections), has been highlighted. To this end, the investigation was carried out by quantifying the effects of GRs on the energy loads and indoor comfort at the single building level, and then by scaling the obtained results to the building stock level.

[7] https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_d_hhq&lang=en (Accessed on 23rd June 2021)

The outcomes of the analysis showed that, with respect to standard roofs, GRs allow a reduction of energy demand for both heating and cooling loads (in the order of 20÷50% and 3÷14% for Esch-sur-Alzette and Palermo, respectively) and an improvement of indoor thermal comfort conditions for the top floor, in terms of reduction of average PMV values for the top floor and ceiling temperatures (attenuation comprised between 2°C for Esch-sur-Alzette and 5°C for Palermo), acting as relievers of the increasingly high outdoor temperatures (also in terms of heatwaves) that are the result of climate change.

Thanks to the abovementioned thermo-hygrometric benefits (which, as showed, can be more or less effective depending on the particular climate classification and construction typology), GRs can also help reduce the size of the technical plants and limit their use, which in turn has a positive impact on the outdoor urban environment inducing various benefits such as the reduction of CO_2 emissions (as confirmed by the results obtained) and the mitigation of the UHI effect, as well as other advantages in terms of air purification and aesthetic aspects.

In conclusion, the analysis performed proved that vegetated roofs seem to represent a valid option in order to improve the climate change resilience of buildings in urban contexts.

The methodology applied represents a first step in the development of procedures developed to assess strategies and solutions aimed at strengthening the resilience of clustered buildings, and this should be further explored and deepened, by also including the economic aspects. In fact, since previous studies have demonstrated that GRs are often not a cost-effective solution at the single building level [104], as a future research development, it would be interesting to estimate their economic impact in a wider urban context.

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Appendix. Buildings' construction features and HVAC schedule

Table A.1, Table A.2, Table A.3.a and Table A.3.b summarize the construction features of interest for the selected buildings in the two towns, where the specific materials in the construction elements were encoded according to the UNI TR 11552 standard [93].

Regarding the characteristics of the external walls, the sequence of materials reported in each row of Table A.3.a indicates the sequence of the layers, going from the external to the internal layers. In Table A.3.b, each row (which refers to a different construction period) shows the sequence of the layers going from the inside to the outside.

The schedule used for the HVAC system is reported below:

- The HVAC running periods are 15 October to 14 April and 15 April to 14 October for the heating and cooling circuits, respectively [96].
- The setpoint temperatures are 21°C and 25°C for heating and for cooling systems, respectively. These values have been chosen by adding or subtracting 1°C from the heating season minimum value (20°C) and cooling season maximum value (26°C) suggested by [97] in table B.5 for Category II.

Table A.1. Construction features for the selected buildings in Palermo.

Construction period	Building ID	Glazing type	Opaque elements material codes* from *UNI TR 11552 standard* [93]			
			External walls	**Floor**	**Ground floor**	**Roof**
< 1945	IT_PA_I_01	double	*MPI 03*	*SOL 02*	*SOL 08*	*COP 01*
	IT_PA_I_02	single	*MPI 03*	*SOL 02*	*SOL 08*	*COP 01*
1946-1971	IT_PA_II_03	double	*MCO 03*	*SOL 02*	*SOL 08*	*COP 01*
	IT_PA_II_04	double	*MPI 03*	*SOL 02*	*SOL 08*	*COP 01*
1972-1991	IT_PA_III_05	double	*MCO 03*	*SOL 02*	*SOL 07*	*COP 01*
	IT_PA_III_06	double	*MCO 03*	*SOL 02*	*SOL 07*	*COP 01*
	IT_PA_III_07	single	*MPI 03*	*SOL 02*	*SOL 07*	*COP 01*
> 1991	IT_PA_IV_08	double	*MCO 03*	*SOL04*	*SOL 07*	*COP 01*

Table A.2. Opaque elements material codes as reported in the UNI TR 11552 standard [93].

Element	Code	Material sequence
External wall	*MPI 03*	Internal plaster Tuff blocks External plaster

	MCO 03	Internal plaster Concrete blocks External plaster
Floor slab	*SOL 02*	Internal stoneware floor Cement mortar Lightweight concrete screed Cement mortar Concrete slab External plaster
	SOL 04	Internal stoneware flooring Cement mortar Lightweight concrete screed Cement mortar Reinforced concrete Concrete slab External plaster
Ground slab	*SOL 07*	Internal stoneware flooring Cement mortar Ordinary concrete screed Reinforced concrete (casting) External plaster
	SOL 08	Internal stoneware flooring Cement mortar Lightweight concrete Scree - river pebbles
Roof	*COP 01*	Internal plaster Concrete slab Reinforced concrete Cement mortar Ordinary concrete screed Bituminous waterproof membrane

Table A.3.a. Construction features for the selected buildings in Esch-sur-Alzette (a).

Construction period	Building ID	Glazing type	Opaque elements materials (1) External walls			
< 1949	LU_Esch_I_01	single	lime	calcar stone	gypsum	
	LU_Esch_I_02	single	mortar	brick	gypsum	
1950-1968	LU_Esch_II_03	single	lime	slag cement block	gypsum	
	LU_Esch_II_04	single	mortar			
1969-1994	LU_Esch_III_05	double	lime	concrete block	insulation	gypsum
	LU_Esch_III_06	double	mortar		mix	
> 1995	LU_Esch_IV_07	double	lime	concrete block	insulation	gypsum
	LU_Esch_IV_08	double	mortar		mix	

Table A.3.b. Construction features for the selected buildings in Esch-sur-Alzette (b).

Opaque element materials (2)										
Roof						**Ground floor**				
wood (hard)	wood (board)	insulation mix	bitumen	tiles		insulation mix	wood (board)	cement screed	tiles	
lime mortar	reinforced concrete	cement screed	bitumen	gravel		reinforced concrete	cement screed	bitumen	tiles	
lime mortar	reinforced concrete	insulation mix	cement screed	bitumen	gravel	reinforced concrete	cement screed	insulation mix	bitumen	tiles
lime mortar	reinforced concrete	insulation mix	cement screed	bitumen	gravel	reinforced concrete	cement screed	insulation mix	bitumen	tiles

In the following, some additional details related to the building energy modelling are given:

- a ventilation rate of 40 m^3/h per person was used, which based on our assumptions, corresponds to a value of 1.8 m^3/h per of apartment square metre;
- a 0.7 absorption coefficient was used for all the surface materials;
- the glazing surfaces of the buildings were generated automatically on the basis of the data available for the window-to-wall ratio;
- the whole average internal gain is equal to 3.9 W/m^2 (considering equipment, lights and people);
- the R-values of the walls fall in the range of 0.50÷2.78 m^2K/W, while those of the roofs are in the range of 0.44÷4.61 m^2K/W and those of the ground floor are in the range of 0.38÷3.13 m^2K/W.

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