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Research Article

Do green roofs really provide significant energy saving in a Mediterranean climate? Critical evaluation based on different case studies

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Abstract Green roofs represent a growing technology that is spreading increasingly and rapidly throughout the building sector. The latest national and international regulations are promoting their application for refurbishments and new buildings to increase the energy efficiency of the building stock. In recent years, vegetative coverings have been studied to demonstrate their multiple benefits, such as the reduction of the urban heat island phenomenon and the increase in the albedo of cities. On the contrary, this study aims to verify the actual benefit of applying a green roof on a sloped cover compared with installing a highly insulated tiled roof. The EnergyPlus tool has been used to perform dynamic analyses, which has allowed to understand the behavior of two different stratigraphies in accordance with weather conditions, rain, and irrigation profiles. Results have shown that the installation of a green roof cannot always be considered the best solution for reducing building energy consumption, especially if compared with a classic highly insulated clay tile roof. In terms of summer air conditioning, the maximum saving is 0.72 kWh/m^2. The presence of water in the soil has also been proven a crucial factor.

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Abbreviations

EPBD	European Performance of Buildings Directive
NZEBs	Net zero-energy buildings
nZEBs	Nearly zero-energy buildings
CAM	Minimum Environmental Criteria (in Italian)
DM	Ministerial Decree
LCA	Life cycle approach
BPS	Building performance simulation
EP	EnergyPlus
IDF	Input data file
CSV	Comma-separated value
CTI	Thermotechnical Committee for Energy and Environment (in Italian)
TY	Typical year
HY	Historical year
UHI	Urban heat island

1. Introduction

In recent years, new construction techniques have been designed and implemented due to the urgent need to improve the international building stock and reduce the production of CO_2 in the atmosphere. Green roofs, also known as eco-roofs, are among these techniques.

Several countries, following the guidelines issued by the European Parliament via the EPBD (European Parliament, 2010) and its recent amendment (European Parliament, 2018), encourage the efficiency of housing to reach the ambitious levels of nearly zero-energy buildings or even net zero-energy buildings. They adopt a massive policy aimed at refurbishing existing buildings and renovating new buildings with green roofs, without making any wide and relevant implementation (Versini et al., 2020).

In Italy, the Action Plan for the environmental sustainability of consumption aims to reduce the environmental impact of new buildings and increase the number of green contracts. Accordingly, the Ministerial Decree (DM) 24/12/2015 (Ministeroe della Tutela del TerritorioMare, 2016) defined the Minimum Environmental Criteria (CAM in Italian) for the assignment of design services and works for new constructions; the last update, DM 11/10/2017 (Ministero dell'Ambiente e della Tutela del Territorio e del Mare, 2017), specified that the use of green roofs must be preferred for roofing.

Concerning environmental benefits, several studies have demonstrated the benefits that green roofs produce on the ecosystem. In large cities, one of the greatest environmental problems is the continuous increase in temperature due to the urban heat island (UHI) phenomenon, which places the most vulnerable groups of the population in danger and amplifies the pollution problems. The use of vegetation above building rooftops is the most useful technology to increase the albedo of cities (Santamouris, 2014; Suter et al., 2017). Bevilacqua et al. (2017) have shown that in a southern Mediterranean climate, a green roof can maintain the surface temperature that is between 57% and 63% lower than that of a traditional roof in June owing to the phenomenon of evapotranspiration. Its function as an air filter has also been demonstrated, with the resulting reduction in pollution (Baik et al., 2012). Versini et al. (2016) have shown that the implementation of a green roof on 100% of a building's roof results in a decrease between 30% and 60% in water peak discharge, reducing the risk of sewage overflow; a similar result has also been confirmed by Piro et al. (2018), who have detected a retained volume of 57.5%. Madre et al. (2014) have also demonstrated the importance of green roofs for wild urban flora, protecting the biodiversity of cities.

The wide optimism and the spread of this technology, supported by various environmental reasons, some of which were previously mentioned, have, however, overlooked the real benefit in reducing building energy demand; depending on climatic conditions, a green roof could be irrelevant or even detrimental (Susca, 2019). Case study results have confirmed that buildings built in accordance with new strict energy regulations, with high levels of insulation, achieve moderate benefits from the use of a green roof rather than a classic well-insulated pitched roof (Gargari et al., 2016a); investigating every parameter of the green roof and analyzing every detail are important. Therefore, every aspect, such as the materials used, stratigraphies, sedum type, and, specially, the building location and climatic conditions, must be considered.

From a life cycle approach (LCA) assessment combining the different factors, as listed previously, with the moderate to high maintenance requirements of green roofs, the impact of a green roof does not always differ significantly from that of a traditional roof when it is built using recycled materials (Gargari et al., 2016b).

Various approaches and many studies have been carried out on the thermal performance of green roofs in different locations, with the different aims to validate the results of simulations with physical models (Ávila-Hernández et al., 2020; Niachou et al., 2001), to apply direct measurements to study the different parameters associated with energy behavior by using scale models (Jiang and Tang, 2017; Collins et al., 2017; Coutts et al., 2013; Lisi et al., 2018; Tan et al., 2017) or real size mookups installed on a rooftop (Bevilacqua et al., 2020; Tang and Zheng, 2019; Porcaro et al., 2019; D'Orazio et al., 2012; Mutani and Marchetti, 2015; Korol and Shushunova, 2016; Tang and Qu, 2016; Silva et al., 2016), or to refine and understand the influences of the parameters of vegetative roofs, such as leaf area index (LAI), soil height, and suitable plant species (Peri et al., 2016; He et al., 2017; Eksi et al., 2017; Zhao et al., 2013).

All building regulations share the widespread optimism about the benefits provided by using green roofs, almost forcing their application; each case should be thoroughly analyzed individually to realize at least an LCA analysis (Antonio et al., 2015; Saiz et al., 2006).

The purpose of this study is to perform hourly dynamic energy simulations during a few significant weeks over the summer and winter seasons of building use. An edifice, built with a green roof or with a classic clay tile roof, has been studied using the high-resolution building energy simulation program EnergyPlus (EP), considering all the parameters influencing the real behavior of the building. Previous studies have mainly involved the energy aspects of two technical solutions, without considering environmental aspects, such as the reduction of the UHI phenomenon. In this study, the edifice has been placed and analyzed in three different Italian cities, with three distinctive climatic and meteorological characteristics (solar radiation, rain profile, wind speed, humidity, etc.). Furthermore, different irrigation profiles have been simulated.

This study may be valuable in enriching the scientific discussion on the use of this particular technology, with quantitative evaluations. The quantitative examples provided in this paper can be a valid indication for those who have to make choices in the early stages of design, opting or not to use green roofs in Mediterranean locations.

2. Methodology

2.1. Overview

In this study, the actual thermal performance of a green roof in different climatic situations has been compared with the performance of a well-insulated (in accordance with the Italian energy regulations) traditional clay roof. The study has been performed in three Italian cities (Bolzano, Pisa, and Palermo) located in three different latitudes (Table 1).

The comparison has been made on the basis of the results of a dynamic simulation campaign performed using the EP tool (US Department of Energy, 2016). EP is a program that allows performing dynamic analyses of the thermal behavior of buildings by using input data files and providing all the hourly energy data collected in a CSV file as output; all calculation methods are explained in detail in the software "Engineering Reference" (US Department of Energy, 2016).

Several authors have validated the tool with experimental data. For instance, Ávila-Hernández et al. (2020) have compared on-site measurements of surface temperatures inside a green roof and EnergyPlus output temperatures, and they have found a maximum error of 2.17%.

2.2. Building main features

A standard building, corresponding to the common properties of an Italian building, with different types of roofs has been chosen. Accordingly, the edifice named "case study 9 A"; provided by the Italian Thermotechnical Committee for Energy and Environment (CTI) has been modeled (Italian Thermotechnical Committee for Energy and Environment, 2019); this building has been released to validate the software used to calculate the energy performance of buildings by estimating heating and cooling loads in accordance with national energy regulations. It is a parallelepiped residential apartment building that is north—south oriented, has parallel facades, and is composed of 12 residential units distributed over 4 floors (ground floor and 3 floors aboveground). Figs. 1 and 2 show a typical architectural plan and the section and a three-dimensional representation of the building object of the analysis, respectively.

The building has been slightly modified, particularly concerning the envelope stratigraphies to be in compliance with the thermal transmittance (U) limits set by Italian DM 26/06/2015 in force (Ministero dello Sviluppo Economico, 2015). It has been chosen to simulate the building in the three cities with the same stratigraphy, given that thermal transmittance is not the only value that indicates dynamic thermal behavior; the results would have been less clear and readable by modifying the stratigraphies. Table 2 shows the principal geometric and design features of the building. Regarding the two different roofing systems, the detailed design and thermal features used are shown in Fig. 3, Table 3, and Table 4.

Both stratigraphies have equal transmittance (0.233 W/(m^2·K) for the green roof and 0.223 W/(m^2·K) for the tile roof), although the actual dynamic performance is also influenced by other parameters, especially for the green roof. Therefore, a specific EP green roof module (US Department of Energy, 2016) has been used to model and manage all vegetation details. A specific section of the software has been implemented to simulate the phenomena characterizing green covering, such as evapotranspiration, water storage in the ground, and leaf covering from direct solar radiation. An extensive roof has been selected as a representative and diffuse green roof technology, as typically used for large, nonpractical areas, with a plant species that requires minimal maintenance (once or twice a year). Accordingly, the green roof has been simulated with an 8 cm soil layer planted with *Aptenia lancifolia*, with an experimental LAI value of 1.26 (tested in the Italian climate) (Peri et al., 2016).

The building has been divided into thermal zones, one for each flat plus the stairwell; the apartments are air conditioned, but the stairwell is not.

The internal gains, occupation, equipment, and lights have been set to zero because they would have influenced the actual thermal behavior of the roof, according to the authors. However, a 24/7 constant heating set point of 20.0 °C and a 24/7 cooling set point of 26.0 °C have been set. Furthermore, standard infiltration and ventilation values have been set, as indicated by ASHRAE in standard 62.1 (ASHRAE, 2016) and shared by NREL; infiltration has been set to 1 (l/m^2·s) and ventilation to 0.3 (l/m^2·s).

2.3. Geographical location

Italy is a country where cities are located at different latitudes, and the influence of the sea or mountains causes different climate profiles. To consider such differences, simulations have been carried out by placing the same building in three cities, namely, Palermo, Pisa, and

Table 1 Geographical coordinates of the three cities where the simulations have been performed.

	Geographical coordinates	
Bolzano	Latitudes	**46°29′36″96 N**
	Longitude	11°20′4″56 E
Pisa	Latitudes	**43°42′42″48 N**
	Longitude	10°24′52″92 E
Palermo	Latitudes	**38°6′43″56 N**
	Longitude	13°20′11″76 E

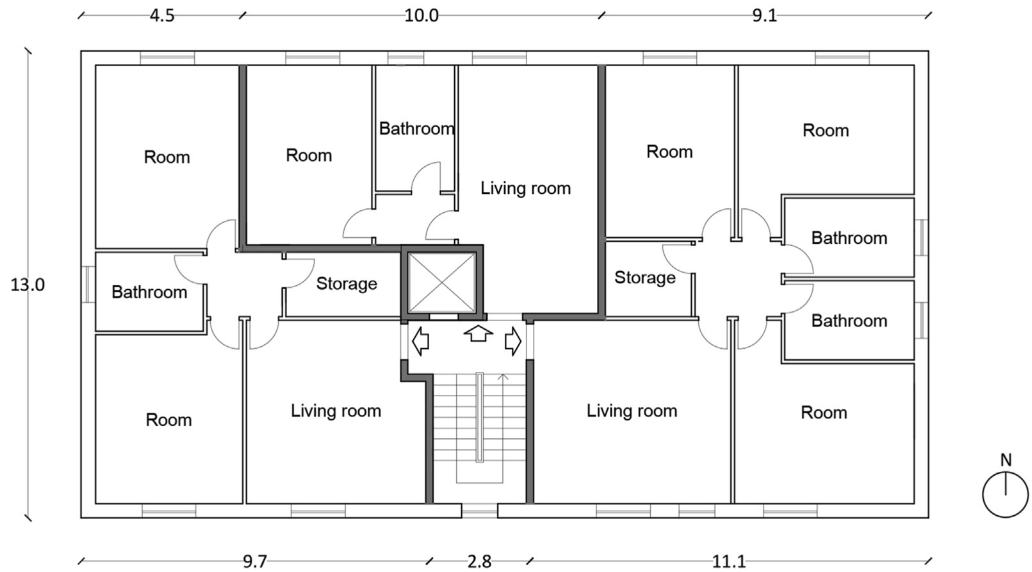

Fig. 1 Typical architectural plan of the selected building.

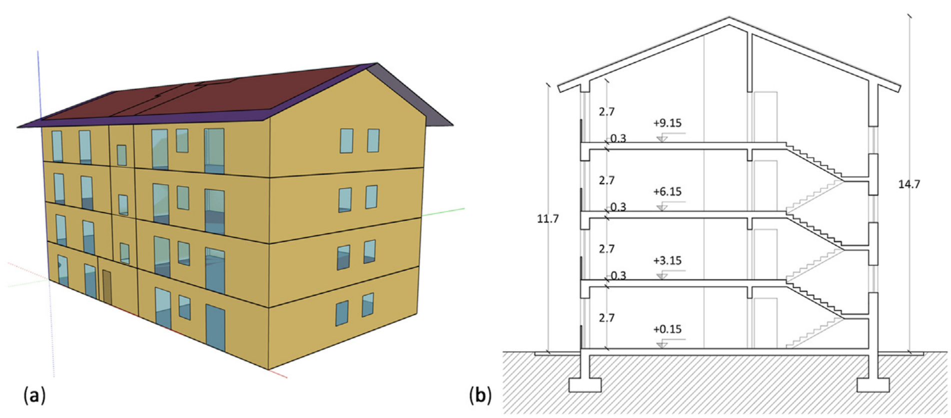

Fig. 2 (a) Building perspective; (b) Cross section of the selected building.

Bolzano, located at different latitudes and situated in different climate zones (Presidente della Repubblica, 1993; UNI - Italian Standards Institution, 2016). To demonstrate the different temperature trends and rainfall profiles, Fig. 4 shows the outputs of the climate files used for the simulations, displaying the sum of monthly precipitation on the main axis and the monthly average temperatures on the secondary one.

The weather files, which belong to the Italian climatic data collection "Gianni De Giorgio" (IGDG), have been chosen from those made available on the EP website, developed for use in simulating renewable energy technologies (De Giorgio, 1984).

As expected, temperatures are higher in Palermo and lower in Pisa and Bolzano, especially during the winter months. Palermo is a city where the season is dryer compared with the two other cities, with 581 mm of rain per year, dominated by short duration and high-intensity rainfall. Pisa (1080 mm) and Bolzano (922 mm) have different monthly distributions but similar precipitation quantities.

The weather files provided by EP are reliable; they belong to the IGDG collection, but these climatic files have been elaborated on the basis of observations made between 1951 and 1970 (Murano et al., 2016). The global warming that the world has been experiencing in recent decades makes these data obsolete, especially for a summer period analysis. For designing such climate files, the registered data have been elaborated to have a typical year (TY) in accordance with EN ISO 15927—4 (ISO, 2005), which consists of 12 characteristic months chosen from a database of meteorological data for a period that should be at least 10 years. The TY should represent the average values of the most important climate parameters. However, these re-elaborations do not allow to simulate a particularly hot year or week because they represent average values that exclude peaks. Therefore, dynamic simulations have been performed in the cities of Palermo, Pisa, and Bolzano. A historical year (HY)-type weather file with the specific climate data of summer 2019 has been used (dry and wet bulb temperature, atmospheric pressure, relative humidity, intensity of solar radiation, wind speed, and rain intensity

Table 2 Geometric and design features of the selected building.

Building characteristics		U limit values
Geometric features		
Length of North/Sud front	23.6 m	
Length of Est/West front	13.0 m	
Floor to floor height	3.0 m	
Average floor surface	261.0 m^2	
Roof pitch	20.0°	
Structural type	Heavyweight brick masonry with hollowbricks roof	
External wall transmittance	0.257 W/(m^2·K)	0.28 W/(m^2·K)
Internal wall transmittance	0.74 W/(m^2·K)	—
Roof transmittance	Various W/(m^2·K)	0.24 W/(m^2·K)
Ground floor transmittance	0.285 W/(m^2·K)	0.29 W/(m^2·K)
Internal floor transmittance	0.74 W/(m^2·K)	—
Type of windows	Low emissivity double glazed with Argon and PVC frame	
Windows transmittance	1.333 W/(m^2·K)	1.4 W/(m^2·K)
SHGC (Solar Heat Gain Coefficient)	0.536	
Total north facing windows surface	70.8 m^2	
Total south facing windows surface	63.4 m^2	
Total east facing windows surface	9.6 m^2	
Total west facing windows surface	4.8 m^2	

in mm/h). A similar study has been conducted by Siu et al. (Siu and Liao, 2020). The graphs in Fig. 5 show the comparison among the temperature trends.

The 2019 summer weeks were warmer in all three cities. The difference was more evident in Bolzano, where the weekly average increased from 18.8 °C to 26.9 °C. In Pisa, it increased by 2.9 °C from 23.9 °C to 26.9 °C. In Palermo, it increased from 25.5 °C to 27.5 °C. These data confirm the hypothesis that the development of extreme weather files could predict the impact assessment of climate change on buildings accurately (Nik and Arfvidsson, 2017).

The amount of water in the soil has been considered an important variable for this study. Hence, the green roof has been simulated with three different combinations of natural rain and irrigation:

- Natural rainfall, as calculated from the cities' weather files
- Automatic irrigation during daily hours
- Neither precipitation nor irrigation, i.e., the green roof has no water supply

The amount of water distributed by irrigation has been set in accordance with the amount required to feed the plants daily, i.e., from 3 l/m^2 during the winter months to 6 l/m^2 in the summer months.

3. Results and discussion

The most appropriate outputs have been chosen from those made available by EP.

- Site outdoor air dry-bulb temperature (°C)
- Zone mean air temperature (°C)

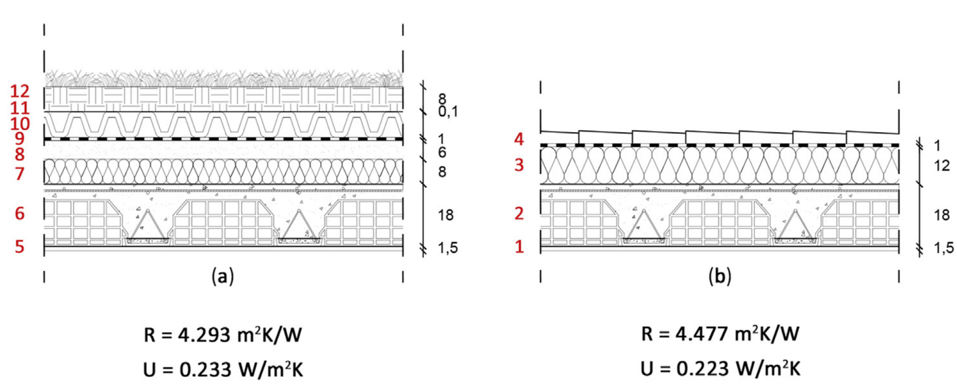

Fig. 3 (a) Green roof stratigraphy; (b) tile roof stratigraphy.

Table 3 Tile roof features.

Tile roof - layers description		Thickness (s) (m)	Thermal conductivity (λ) (W/m·K)	Thermal resistance (R) (m^2·K/W)	Specific heat (c) (J/kg·K)	Density (ρ) (kg/m^3)
1	Plaster, chalk lime	0.015	0.900	/	1000	1800
2	Concrete and brick floor slab	0.180	/	0.300	840	950
3	Insulation Greydur Top B	0.120	0.030	/	1450	26
4	Shingles	0.020	1.000	/	800	2000

Table 4 Green roof features.

Green roof - layers description		Thickness (s) (m)	Thermal conductivity (λ) (W/m·K)	Thermal resistance (R) (m^2·K/W)	Specific heat (c) (J/kg·K)	Density (ρ) (kg/m^3)
5	Plaster, chalk lime	0.015	0.900	/	1000	1800
6	Concrete and brick floor slab	0.180	/	0.300	840	950
7	Insulation Greydur Top B	0.080	0.030	/	1450	26
8	Slope screed	0.060	0.396	/	1000	72
9	Root-proof waterproofing	0.010	0.230	/	900	11
10	Drainage FSD 20	0.082	/	0.710	1200	25
11	Filter stabilfilter SFE	0.001	0.220	/	900	163
12	Roof Soil	0.080	0.310	/	1348	750

- Zone ideal loads supply air total heating and cooling rate (Wh)
- Current and cumulative precipitation depth (m)
- Current and cumulative irrigation depth (m)
- Green roof soil root moisture ratio
- Surface outside and inside face temperature (°C)
- Surface outside and inside face conduction heat transfer rate per area (Wh)

The results of the energy needs and indoor temperatures shown below are related to one of the top floor thermal zones, directly under the roof layer. Specifically, the apartment is exposed to east.

3.1. Main simulations and thermal evaluation

Two significant weeks, namely, one winter week (from January 30th to February 5th) and one summer week (from July 12th to July 18th), have been chosen to display the results. The choice of the two severe weeks has been made to demonstrate the real thermal behavior in different climates; the behavior highlighted in those two weeks is qualitatively the same in the others, even if mitigated in intensity. Thus, we have considered to show only the two weeks. The variable and chaotic meteorological characteristics make it necessary to switch from hourly results to weekly values to avoid studying a particularly hot and dry day or a cold and humid one.

Figs. 6—8 show the weekly thermal energy transferred by conduction on the inward and outward surfaces of the roofs. Tables 5—7 indicate the weekly averaged temperatures at different layers, weekly averaged humidity, and weekly energy consumption. For representation purposes, outward flows are shown with a negative sign and inward flows with a positive sign.

Moreover, diagrams that relate the environmental temperatures and soil humidity of the green roof as weekly average, the weekly thermal energy transferred by conduction on the inward and outward surfaces (the same as the previous charts), and the weekly heating and cooling consumptions have been elaborated. Graphs showing the hourly trends of all the days of the two selected weeks are listed in the Supplementary Materials (Fig. S1 to Fig. S6). For any of them and for each of the three cities, four graphs have been elaborated:

- Two comparing the surface temperatures with the outdoor temperature trend, also indicating the hourly rainfall volume (in mm)
- Two comparing the thermal energy transferred by different roof types, designed with diverse rain and irrigation profiles

Diagrams with the weekly values in Palermo, Pisa, and Bolzano are shown in the Appendix (Figures A1, A2, and A3); any of them includes the results provided for green and tile roofs simulated with natural rain, the green roof with daily irrigation profile, and the green roof without water.

The simulation results reveal considerable differences. In the winter, weekly thermal energies transferred on inward and outward surfaces are negative (outward) in all three cities, with different values. In summer, we note

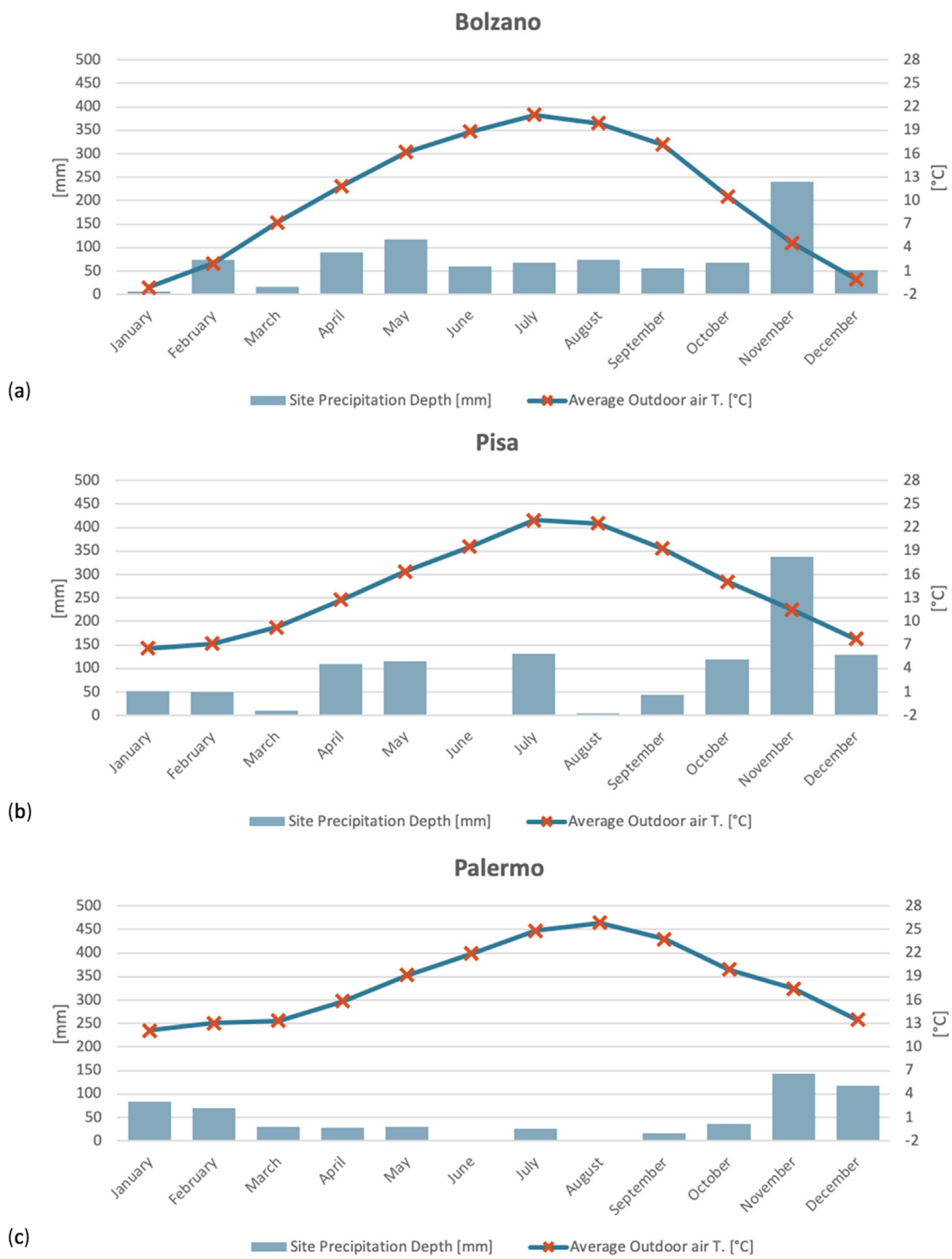

Fig. 4 Graphs showing the climatic conditions of Bolzano (a), Pisa (b), and Palermo (c).

different phenomena. In Palermo, where the outdoor climate is particularly hot, weekly thermal energies transferred on inward and outward surfaces are all positive (inward). In Pisa, the same thermal energies are all positive, as in Palermo, with lower absolute values, except in the case of a wet green roof with automatic irrigation that maintains a soil moisture value of 35%, where the weekly transferred thermal energy is positive on inward and outward surfaces. In Bolzano, the low external temperatures in the evening result in a sign inversion of the thermal energy transferred during the week, and it is therefore directed outward on the external surface (negative) and inward on the internal surface (positive).

Numerically, the roof type that performs best in the winter season is the nonirrigated green roof, i.e., the roof for which minimal heat loss occurs. During the summer, positive (inward) values of weekly thermal energy transferred to the building are low in irrigated roofs; consequently, the soil has a high humidity level. Actually, in Pisa, the thermal energy transferred is turned outward.

The thermal performance of the four winter configurations is remarkably similar, with no major differences in thermal energy transferred and consumption in all of the three cities. Theoretically, we can conclude that for the best result, the vegetation shall be irrigated to a minimum necessary to keep the plants healthy, but results would not differ considerably in terms of thermal flow, from a standard, well-insulated, clay roof tile.

In the summer, substantial differences in inward thermal energies exist. The best practice is to maintain the soil wet

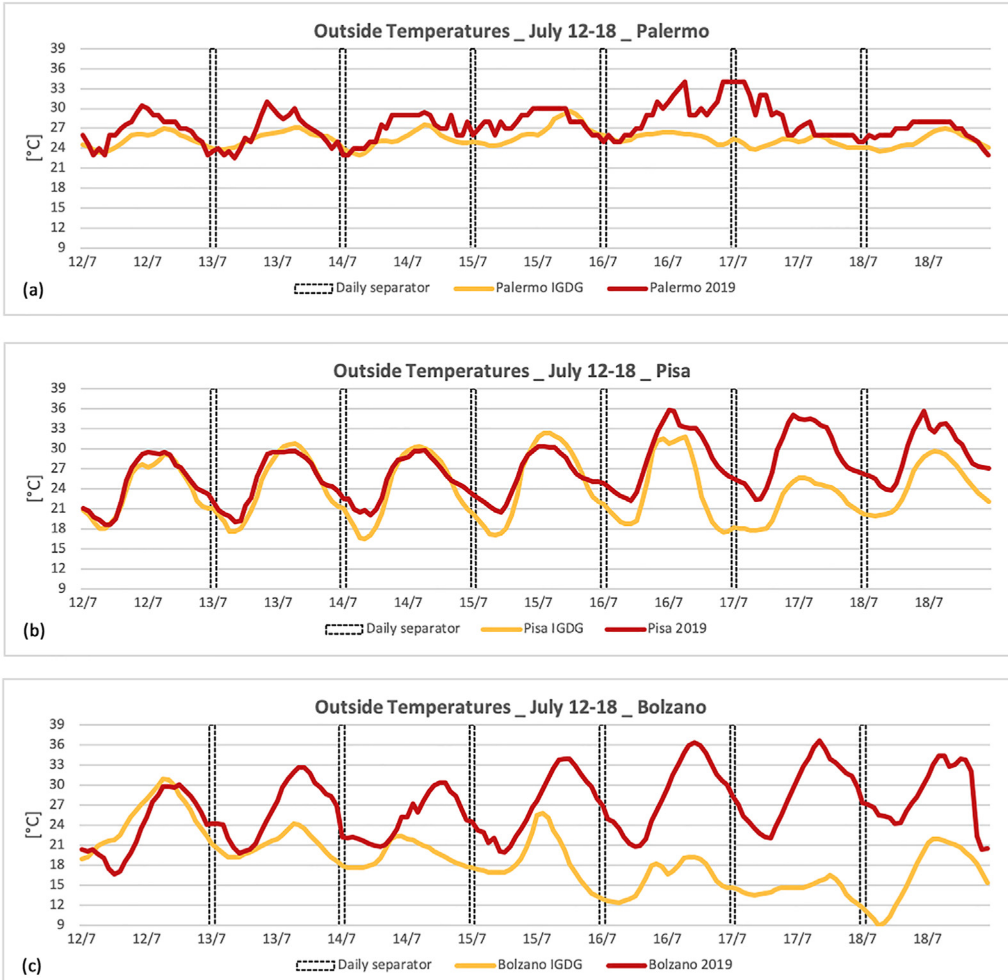

Fig. 5 Comparison between outside temperature trends for a week of July 2019 and for that contained in the IGDG weather file for Palermo (a), Pisa (b), and Bolzano (c).

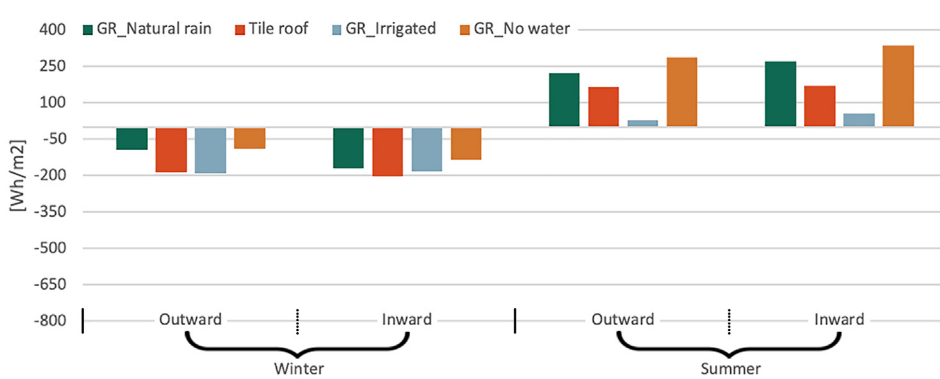

Fig. 6 Charts showing the weekly thermal energy transferred by conduction on the inward and outward surfaces for Palermo in accordance with the IGDG data.

when the evapotranspiration phenomenon increases and intensifies the capacity of the soil to store heat. During summer, a minimum level of irrigation is always necessary because a dry green roof causes approximately twice as much heat to enter the indoor space as a tiled roof, despite having the same thermal transmittance.

Regarding the hourly performance of the different roof types over the course of a day, as shown in the graphs attached in the Supplementary Materials, all green roofs having more thermal mass cause a longer time lag of a few hours compared with the standard tiled roof. The surface temperatures of tiled roofs exposed to the south are always

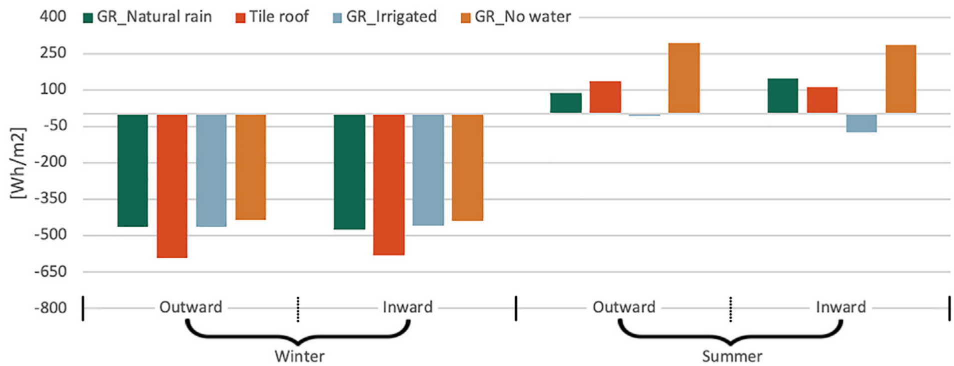

Fig. 7 Charts showing the weekly thermal energy transferred by conduction on the inward and outward surfaces for Pisa in accordance with the IGDG data.

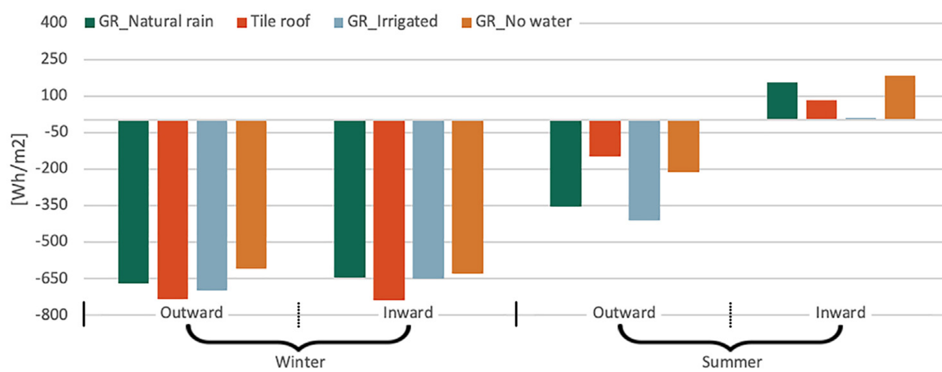

Fig. 8 Charts showing the weekly thermal energy transferred by conduction on the inward and outward surfaces for Bolzano in accordance with the IGDG data.

Table 5 Weekly averaged temperatures of different layers, weekly averaged humidity and weekly energy consumption, for Palermo according to IGDG data.

	Palermo		GR_Natural rain	Tile roof	GR_Irrigated	GR_No water
Winter	Weekly averaged Temperature (°C)	Outside air T	14.3	14.3	14.3	14.3
		GR Vegeta. T	14.9	/	14.9	15.6
		Outside face T	16.3	14.9	15.5	17.0
		Inside face T	19.9	19.9	19.9	20.0
		Internal air T	20.0	20.0	20.0	20.0
	RH (%)	Soil	32.9	/	24.2	1.8
	Energy cons. (kWh/m^2)	Heating	1.68	1.73	1.68	1.65
Summer	Weekly averaged Temperature (°C)	Outside air T	25.5	25.5	25.5	25.5
		GR Vegeta. T	30.1	/	27.8	32.7
		Outside face T	33.8	31.6	28.4	35.6
		Inside face T	27.5	27.3	27.2	27.5
		Internal air T	26.0	26.0	26.0	26.0
	RH (%)	Soil	14.8	/	36.0	1.0
	Energy cons. (kWh/m^2)	Cooling	2.45	2.15	1.87	2.59

high during the daily hours due to solar radiation. In green roofs, particularly in summer, the greater the amount of water in the ground is, the lower the influence of radiation on the roof is; therefore, the lower the surface temperature is.

3.2. Simulations with summer 2019 climate data and thermal evaluation

The summer performance of roofs has been studied again with the new weather file, including the 2019 climate data, to have the actual results on the hottest days of the year.

Table 6 Weekly averaged temperatures of different layers, weekly averaged humidity and weekly energy consumption, for Pisa according to IGDG data.

	Pisa		GR_Natural rain	Tile roof	GR_Irrigated	GR_No water
Winter	Weekly averaged Temperature (°C)	Outside air T	5.5	5.5	5.5	5.5
		GR Vegeta. T	5.6	/	5.7	6.2
		Outside face T	6.6	3.1	6.9	7.5
		Inside face T	18.7	18.6	18.8	18.8
		Internal air T	20.0	20.0	20.0	20.0
	RH (%)	Soil	37.7	/	26.3	3.4
	Energy cons. (kWh/m^2)	Heating	5.46	5.60	5.44	5.42
Summer	Weekly averaged Temperature (°C)	Outside air T	23.9	23.9	23.9	23.9
		GR Vegeta. T	27.3	/	24.8	30.5
		Outside face T	29.9	29.7	25.0	33.1
		Inside face T	26.6	26.5	26.2	26.8
		Internal air T	26.0	26.0	26.0	26.0
	RH (%)	Soil	21.1	/	35.2	1.0
	Energy cons. (kWh/m^2)	Cooling	0.83	0.78	0.61	0.93

Table 7 Weekly averaged temperatures of different layers, weekly averaged humidity and weekly energy consumption, for Bolzano according to IGDG data.

	Bolzano		GR_Natural rain	Tile roof	GR_Irrigated	GR_No water
Winter	Weekly averaged Temperature (°C)	Outside air T	1.7	1.7	1.7	1.7
		GR Vegeta. T	1.5	/	1.5	1.8
		Outside face T	2.1	−1.0	2.0	2.7
		Inside face T	18.3	18.2	18.3	18.3
		Internal air T	20.0	20.0	20.0	20.0
	RH (%)	Soil	27.2	/	26.7	4.9
	Energy cons. (kWh/m^2)	Heating	7.05	7.18	7.05	7.03
Summer	Weekly averaged Temperature (°C)	Outside air T	18.8	18.8	18.8	18.8
		GR Vegeta. T	20.6	/	19.0	21.9
		Outside face T	22.3	21.2	18.9	23.3
		Inside face T	24.9	24.8	24.6	25.0
		Internal air T	26.0	26.0	26.0	26.0
	RH (%)	Soil	21.9	/	37.2	1.0
	Energy cons. (kWh/m^2)	Cooling	0.14	0.13	0.10	0.16

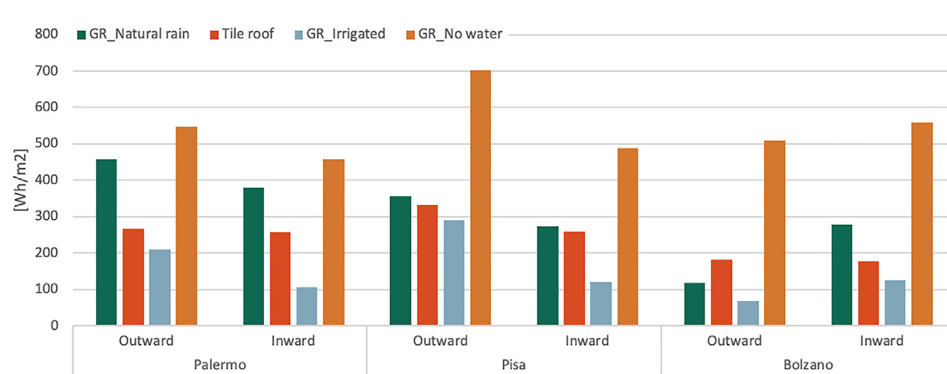

Fig. 9 Charts showing the weekly thermal energy transferred by conduction on inward and outward surfaces for the summer week in accordance with the HY 2019 data.

Table 8 Weekly averaged temperatures of different layers, weekly averaged humidity, and weekly energy consumption for the summer week in accordance with the HY 2019 data.

Palermo		**GR_Natural rain**	**Tile roof**	**GR_Irrigated**	**GR_No water**
Summer weekly averaged Temperature (°C)	Outside air T	27.5	27.5	27.5	27.5
	GR Vegeta. T	33.5	/	30.2	36.3
	Outside face T	37.6	34.7	31	39.8
	Inside face T	27.8	27.6	27.5	27.9
	Internal air T	26.0	26.0	26.0	26.0
RH (%)	Soil	12.4	/	30.4	1.0
Energy cons. (kWh/m^2)	Cooling	3.91	3.63	3.33	4.05
Pisa		**GR_Natural rain**	**Tile roof**	**GR_Irrigated**	**GR_No water**
Summer weekly averaged Temperature (°C)	Outside air T	26.9	26.9	26.9	26.9
	GR Vegeta. T	31.2	/	29.1	37.5
	Outside face T	35.0	35.3	31.5	41.3
	Inside face T	27.7	27.7	27.5	28.0
	Internal air T	26.0	26.0	26.0	26.0
RH (%)	Soil	21.5	/	36.4	1.0
Energy cons. (kWh/m^2)	Cooling	3.25	3.19	2.97	3.59
Bolzano		**GR_Natural rain**	**Tile roof**	**GR_Irrigated**	**GR_No water**
Summer weekly averaged Temperature (°C)	Outside air T	26.8	26.8	26.8	26.8
	GR Vegeta. T	30.4	/	28.5	37.8
	Outside face T	33.8	32.1	30.5	41.6
	Inside face T	27.5	27.3	27.2	27.9
	Internal air T	26.0	26.0	26.0	26.0
RH (%)	Soil	22.5	/	35.3	1.0
Energy cons. (kWh/m^2)	Cooling	2.42	2.29	2.16	2.85

Fig. 9 shows the weekly thermal energies transferred on inward and outward surfaces, and Table 8 indicates the weekly averaged temperatures, weekly averaged humidity, and weekly energy consumption. Moreover, diagrams showing the weekly thermal energies, the sum of energy consumption, and the averages of outdoor temperatures and water content in the soil are provided in the Appendix (Figure A4); graphs with the hourly trends are attached in the Supplementary Materials (Fig. S7 to Fig. S9).

The results show some differences in the heat flow directions that result in diverse values of the weekly thermal energies transferred.

The conclusions made for the previous simulations can also be confirmed in these cases. That is, the configuration that performs best in terms of thermal performance is the wet green roof when constantly irrigated to have a humidity level of 30% or more. As the soil humidity decreases, the thermal insulation qualities of the vegetative roof decrease as well, producing negative results below a water content of approximately 20% and then performing worse than the tiled roof.

The change in weekly thermal energies transferred and cooling needs must be underlined using HY instead of TY. Summer consumptions, indicated in Tables 5–8, increase as follows:

- For Palermo, it increases by 60%.
- For Pisa, it increases by 350%.
- For Bolzano, it increases by 2000%.

Weekly thermal energies transferred change differently depending on the roof type and the amount of water in the

Table 9 Differences between the weekly thermal energy transferred by conduction on the inward and outward surfaces of the different roof configurations, simulated with the different weather files, IGDG and HY 2019.

Differences among weekly thermal energies (Wh/m^2)					
		GR_Natural rain	Tile roof	GR_Irrigated	GR_No water
Surface outside face	Palermo	235	101	181	261
	Pisa	268	196	299	409
	Bolzano	474	332	480	722
Surface inside face	Palermo	110	90	53	121
	Pisa	125	147	194	205
	Bolzano	123	94	118	374

Table 10 Daily irrigation needs, values in l/m^2.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Daily irrigation needs	0	0	1.4	3.0	4.0	5.0	6.0	5.5	3.5	2.0	0	0

ground. Table 9 shows the differences among the flows obtained by simulating with the two climate data, IGDG and HY 2019, divided by external and internal faces.

The increase in inward weekly thermal energy is higher in the cases of dry green roofs, which is confirmed as the worst situation among the four studied. The increase in outside temperatures and, as a consequence, solar radiation, affects less the classic tiled roof, followed by the irrigated green roof. The water content in the soil slightly mitigates the effects of global warming.

3.3. Overview of the water needed to maintain the roof irrigated

The analyses conducted have always confirmed that the wet green roof, well irrigated, is the one that performs best during the warm months. The amount of water inside the soil improves the heat storage capacity and has a positive effect on the evapotranspiration of the green roof, from which the building benefits substantially. On the contrary, the best performance has been obtained in the winter months when the green roof is dry.

How much water would be required yearly to assure the performance of the green roof has been a crucial key of the analysis.

A rainwater storage tank has been designed to reduce tap water consumption. The storage tank has been sized in accordance with E DIN 1989—1: 2000—12, in which the volume of the storage tank can be set indicatively in accordance with the net rainwater supply and the water requirement. The following equation is used to calculate the rain yield "*R*" (UNI - Italian Standards Institution, 2012):

$$R = S \cdot c \cdot H, \quad (1)$$

where "*R*" (*l*) is the rain yield; "*S*" is the projected roof area (m^2); "*c*" is the runoff coefficient, equal to 0.5 for extensive green roofs; "*H*" (mm) is the rainfall height.

The water requirement "F_i" for domestic use related to irrigation for gardening refers to the average annual value of 450 (l/m^2).

The minimum tank volume "*V*" is calculated with the following equation (UNI - Italian Standards Institution, 2012):

$$V = F_c \cdot k, \quad (2)$$

where F_c is the calculation factor, i.e., the smallest value between rain yield "*R*" and water requirement "F_i"; "*k*" is a constant equal to 0.0625 (UNI - Italian Standards Institution, 2012).

The water needed to irrigate 100 m^2 of extensive green roofs has been assumed to calculate. The presize of the storage tank has been calculated using the hourly rainfall heights already used in previous simulations. A tank of 2000 l is necessary in the city of Palermo. In the cities of Pisa and Bolzano, a 3000 l tank is needed due to the high annual rainfall.

Accordingly, hourly simulations have been carried out in all three cities in consideration of the rain that has been accumulated and the water that has been used to irrigate. The amount of tap water to be integrated to satisfy irrigation needs has also been calculated.

The scheduled profile of the quantity of water required for irrigation in relation to the months of the year is shown in Table 10.

Below, Table 11 shows the results of the hourly simulation, displaying the amount of tap water required to supply the irrigation need, not covered by the rainwater collected in the storage.

The tank remains almost always full during the rainiest months (January, February, November, and December) when no irrigation is needed.

The analysis of the results has indicated that using a storage as large as 3000 l has no great benefit, if its only goal is to serve as a supply to the green roof irrigation. The largest difference in tap water consumption has been found in Bolzano, where a 2000 l tank capacity saves only 7665 l compared with the 66,755 l needed throughout the year.

Table 11 Results obtained by simulating the use of water storage tanks of different capacities. Tap water consumed and hours when the tank remained full.

Tank capacity		Palermo	Pisa	Bolzano
1000 l	N° of hours the tank is full	2627	2642	2182
	Consumed tap water (l)	82,690	69,860	66,755
2000 l	N° of hours the tank is full	2289	2211	2040
	Consumed tap water (l)	81,170	65,080	61,720
3000 l	N° of hours the tank is full	2044	2151	1951
	Consumed tap water (l)	80,100	62,770	59,090

4. Conclusions

The purpose of this work was to simulate the thermal behavior of two different types of roofs, a standard pitched clay tiled roof and a green roof, to study and understand their energy performance under diverse climatic and weather conditions. The stratigraphies have been designed to have a very similar transmittance, with a value of 0.23 W/(m^2·k), in accordance with the limits imposed by DM 26/06/2015. To evaluate the influence of a different roof type on the global building energy performance properly, a well-insulated building has been designed, when boundary conditions are the same, except the roof design.

EP has been used to carry out a dynamic hourly energy simulation for studying the building performance in three different Mediterranean cities, Palermo, Pisa, and Bolzano. The tiled roof has been simulated with the climatic conditions of the three cities, while the green roof has been simulated in consideration of city-specific rainfall weather data derived from climate data, combined or not with a scheduled irrigation profile.

Subsequently, the summer thermal behavior has been simulated again with the HY 2019 climate data to understand the effects of climate warming on these types of roofs and the differences with the results obtained using IGDG weather files.

Moreover, three different rainwater storages have been simulated in the three cities to satisfy the need of 100 m^2 *Sedum*. The aim was to reduce the amount of water needed to assure sufficient levels of humidity to the soil. The sustainability value usually associated with the use of green roofs cannot ignore the environmental impact of such a large amount of water needed to keep them properly wet. The cost of installing a storage tank and the cost of the water itself should also be considered.

From the analysis of the results, the following conclusions can be drawn:

1. From a thermal point of view, a green roof cannot always be the best solution. When facing south, the temperatures of the outside face are lower than those of a tiled roof, which warms up due to solar radiation, in winter and summer. Similar observations can be made on the results of building simulations with HY 2019 climate data. The average daily temperature of the dry green roof exceeds the temperature of the roof tiles; therefore, the fluctuation in the temperature of the exterior face is not always reflected in optimal thermal behavior;
2. The energy needs for heating and cooling of the attic do not differ considerably, with a weekly maximum variation of 0.18 kWh/m^2 for heating in Pisa and 0.72 kWh/m^2 for cooling in Palermo;
3. Thermal flows through the roof inward and outward surfaces, on the contrary, show marked differences, essentially due to the amount of soil humidity;
4. In short, the green roof with the lowest percentage of water in the ground is the configuration that perform best in winter; on the contrary, the daily well-irrigated green roof performs best in summer. These results have demonstrated that an extensive green roof requires irrigation during the summertime and in supposed-to-be cold climate, as in the north of Italy; otherwise, its thermal performance would decrease drastically;
5. In terms of comfort and energy consumption, substituting an existing roof by a green roof does not bring much more benefits than installing a classic high-performance roof. Moreover, the green roof involves certain maintenance requirements and considerable use of water to work properly. The Italian meteoric rainfall, even when accumulated in a storage facility, does not allow to cover the irrigation demand of a green roof like the one under study.

The installation of a green roof should not always be considered the best solution; it must be properly designed and simulated in accordance with specific climatic conditions before using it. Very dry summer climates would require the use of substantial water to irrigate it. On the contrary, rainy and cold climates in winter seasons would cause a buildup of water in the ground that would increase the heat that is transferred from the inside to the outside. Therefore, in accordance with the obtained results, the legislative push toward the use of this solution in countries, such as Italy, should be carefully considered and differentiated in accordance with locations and their climate data.

Lastly, currently available weather files could be old and obsolete and could lead to misleading results. Being created using EN ISO 15927-4 directives, they represent TYs, developed excluding hot and cold weather peaks. Research and simulations require updated weather files to predict the impact of climate change on buildings more accurately.

Further studies might be carried out following these topics:

- Measurements of the prototypes of green roofs within a year and their comparison with simulation results
- Separate study of day and night behavior, evaluation of the improvement of summer free cooling, and exploitation of the positive contribution of the thermal wave phase shift due to green roof mass.

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Declaration of competing interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foar.2021.01.006.

Appendix A

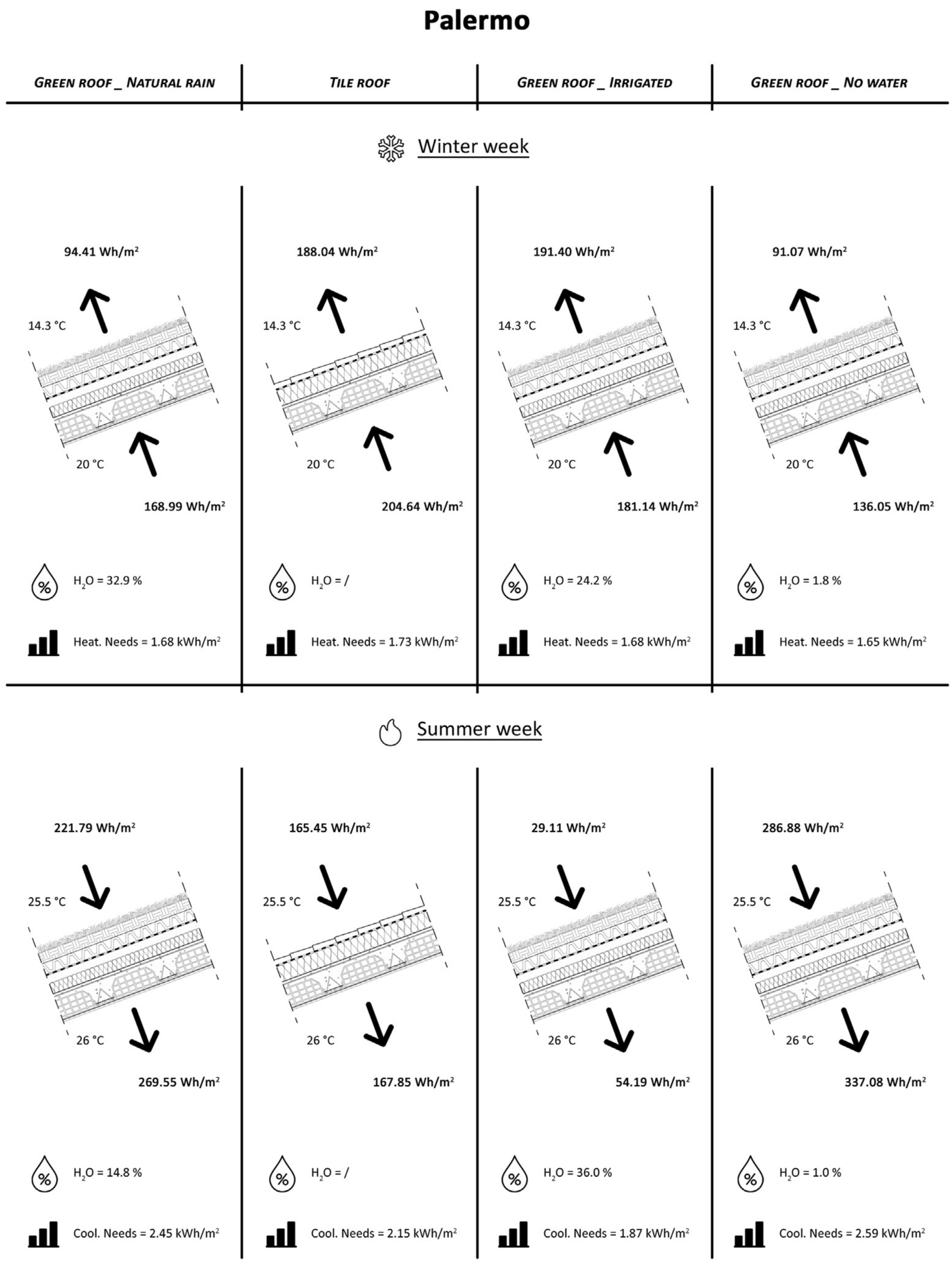

Fig. A1 Diagrams displaying the weekly thermal energy transferred by conduction on the inward and outward surfaces of the different types of roof simulated with the respective rain profiles in Palermo; the illustrations also indicate the average outdoor and indoor temperatures, the average weekly water percentage inside the green roof soil, and the energy needs of the envelope per m^2 of the apartment.

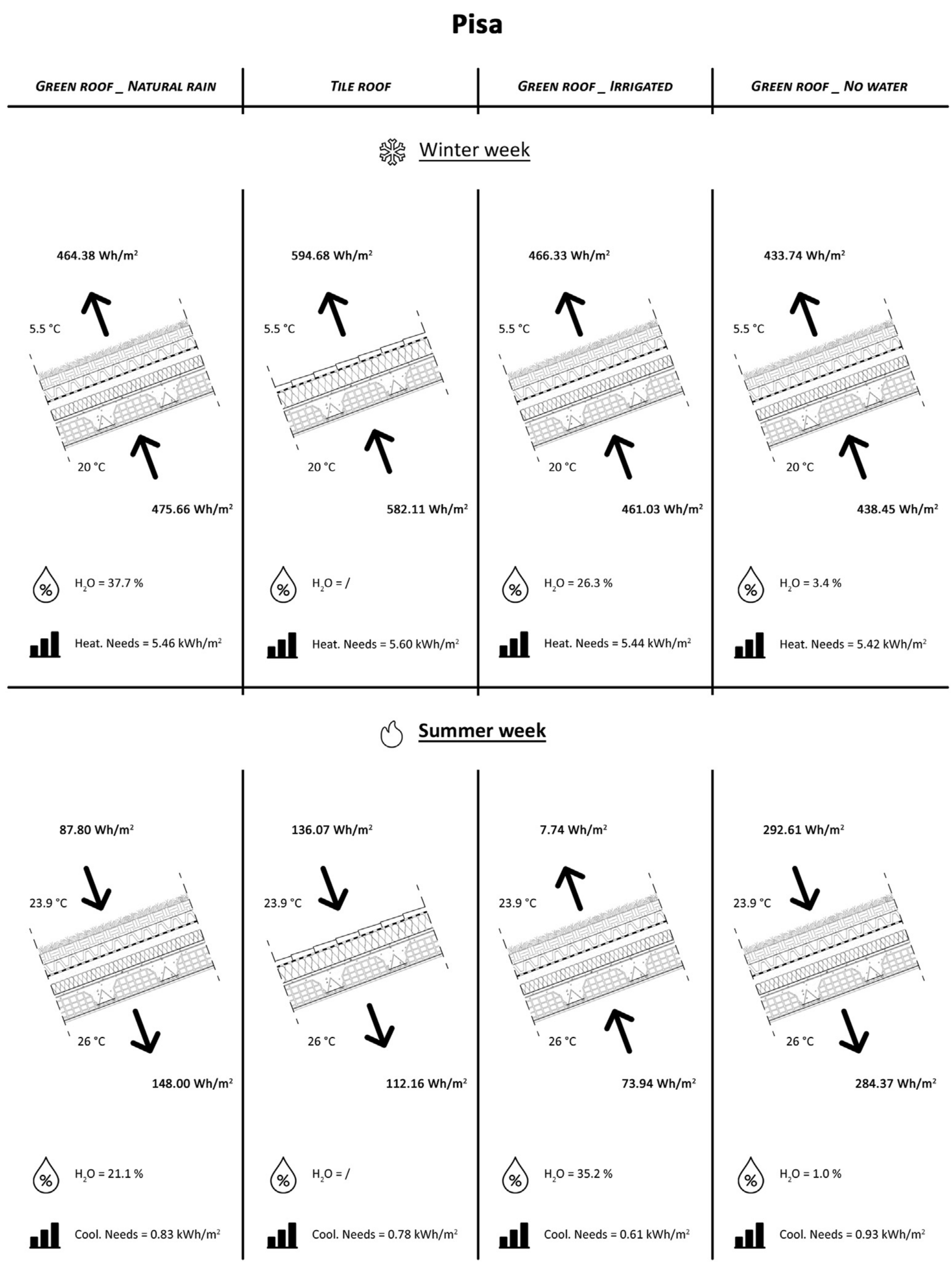

Fig. A2 Diagrams displaying the weekly thermal energy transferred by conduction on the inward and outward surfaces of the different types of roof simulated with the respective rain profiles in Pisa; the illustrations also indicate the average outdoor and indoor temperatures, the average weekly water percentage inside the green roof soil, and the energy needs of the envelope per m^2 of the apartment.

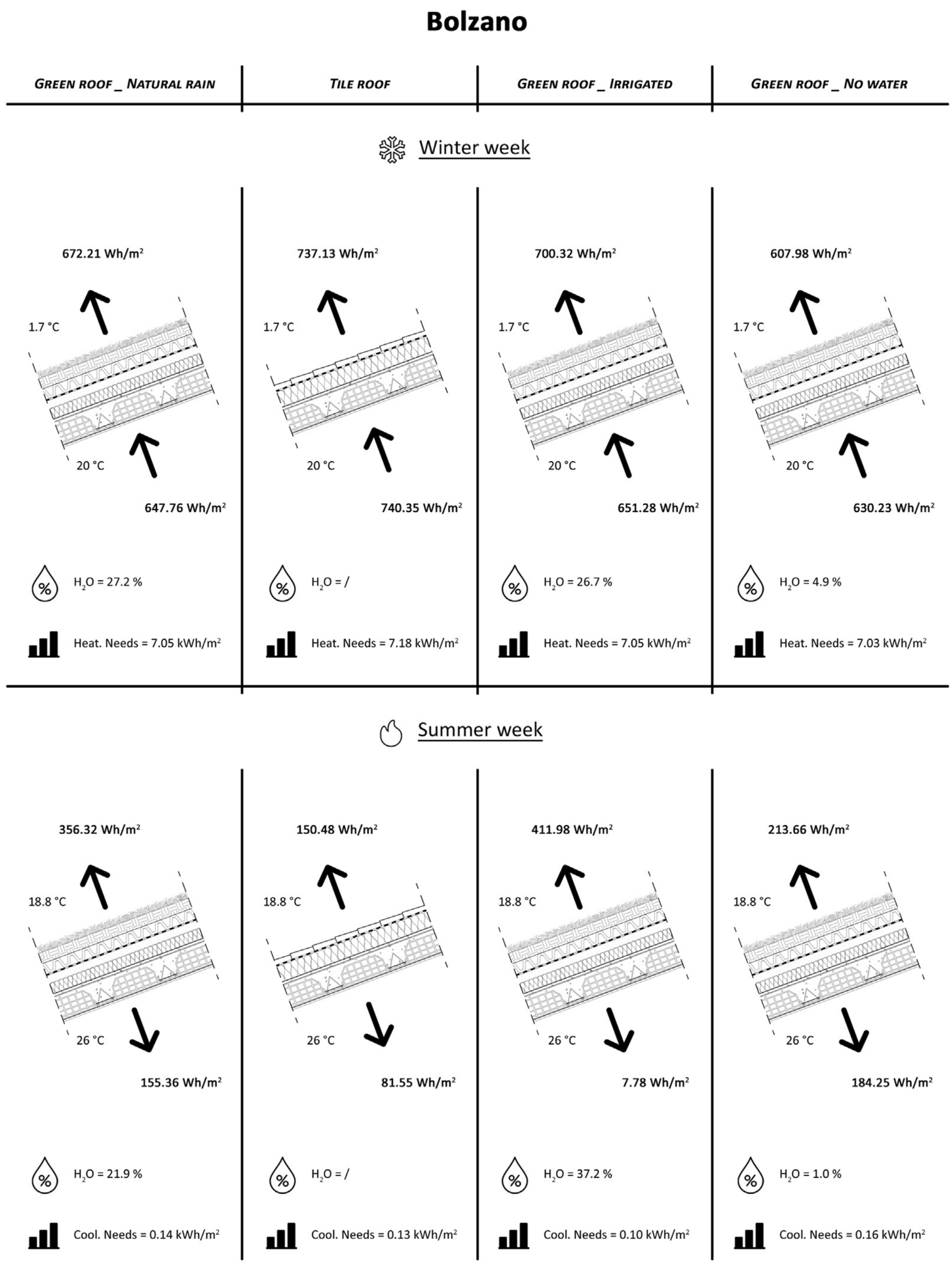

Fig. A3 Diagrams displaying the weekly thermal energy transferred by conduction on the inward and outward surfaces of the different types of roof simulated with the respective rain profiles in Bolzano; the illustrations also indicate the average outdoor and indoor temperatures, the average weekly water percentage inside the green roof soil, and the energy needs of the envelope per m^2 of the apartment.

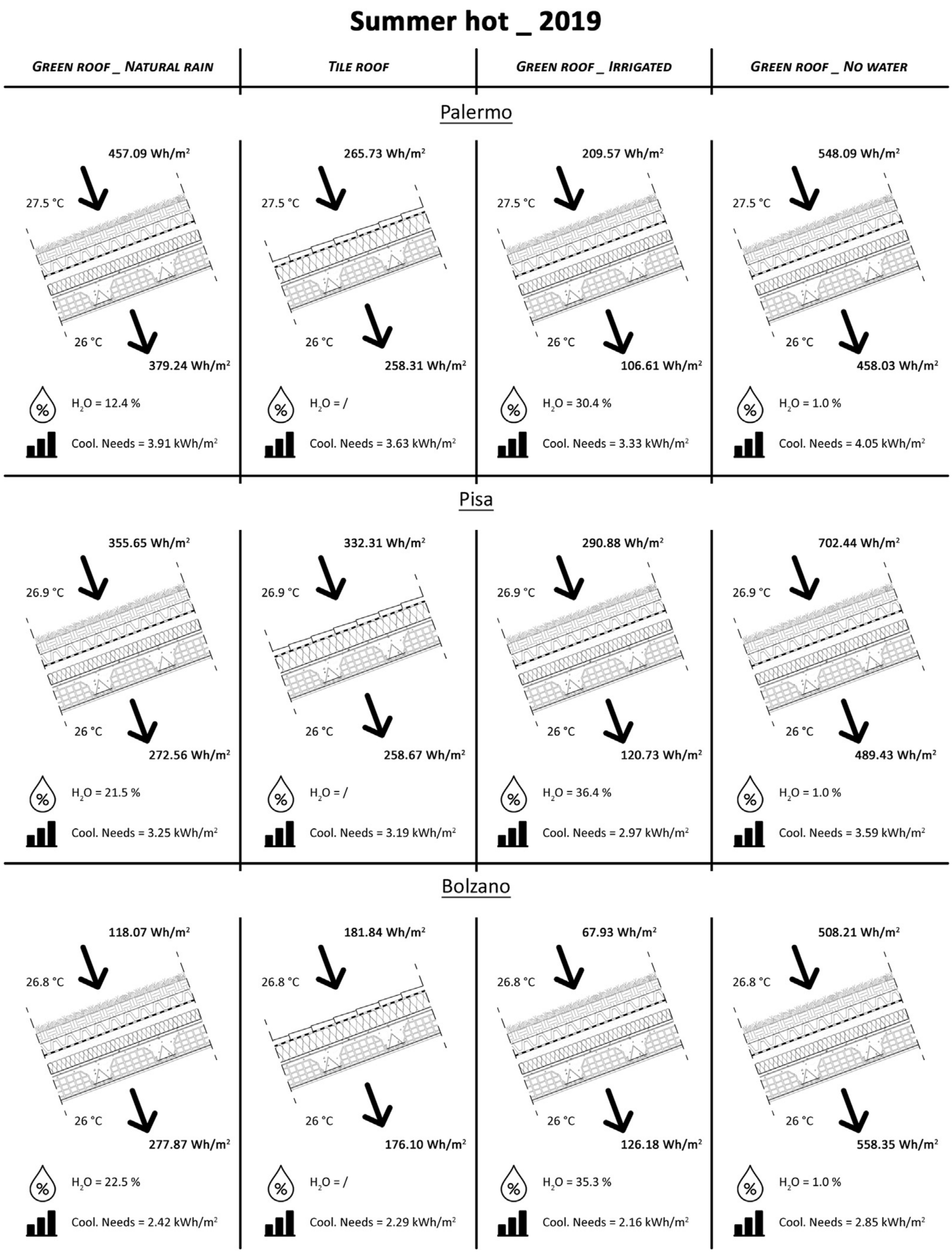

Fig. A4 Diagrams displaying the weekly thermal energy transferred by conduction on the inward and outward surfaces of the different types of roof simulated with the respective rain profiles in Bolzano, Pisa, and Palermo during the summer of 2019; the illustrations also indicate the average outdoor and indoor temperatures, the average weekly water percentage inside the green roof soil, and the energy needs of the envelope per m^2 of the apartment.

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