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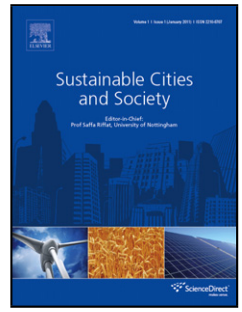

Sensitivity of heating performance of an energy self-sufficient building to climate zone, climate change and HVAC system solutions

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PII: S2210-6707(20)30521-7

DOI: https://doi.org/10.1016/j.scs.2020.102300

Reference: SCS 102300

To appear in: *Sustainable Cities and Society*

Received Date: 29 March 2020

Revised Date: 28 May 2020

Accepted Date: 29 May 2020

Please cite this article as: de Rubeis T, Falasca S, Curci G, Paoletti D, Ambrosini D, Sensitivity of heating performance of an energy self-sufficient building to climate zone, climate change and HVAC system solutions, *Sustainable Cities and Society* (2020), doi: https://doi.org/10.1016/j.scs.2020.102300

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Sensitivity of heating performance of an energy self-sufficient building to climate zone, climate change and HVAC system solutions

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Highlights

- sensitivity of heating performance of energy self-sufficient building is presented
- the use case is analyzed via calibrated EnergyPlus simulation model
- European climate zone, climate change (2050-2080) and HVAC solutions are considered
- the scenarios showed variable energy consumption from 3.0 to 54.2 kWh/m^2yr^1
- climate change will reduce heating demand between -8.5% (2050) and -44.8% (2080)

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Abstract

The building energy behavior is strongly influenced by design choices made to contain energy losses through the envelope and to maximize the overall efficiency of HVAC systems. However, a thorough assessment of energy efficiency measures in relation to weather conditions is necessary. Ongoing climate change requires that design choices be also assessed in relation to projections of their future state.

In this paper, the heating performance of real-world energy self-sufficient building, located in L'Aquila (Italy), is analyzed via calibrated EnergyPlus model. Different interventions are hypothesized for the HVAC system (biomass boiler, air handling unit, condensing gas boiler, air-to-water heat pump, their combinations) and effects are tested in relation to climate zone, by comparing four Italian (L'Aquila, Rome, Palermo, Milan) and two European (Madrid, London) cities, and considering climate change to 2050 and 2080 for the city of L'Aquila.

Results showed how heating system is influenced by weather conditions and what are the best choices in relation to them, ranging from 3.0 $kWhm^{-2}yr^{-1}$, achieved with combination of condensing gas boiler and air handling unit, to 54.2 $kWhm^{-2}yr^{-1}$, obtained with air-to-water heat pump. Finally, future climate change has highlighted significant reductions in heating energy demand between -8.5% (2050) and -44.8% (2080).

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Keywords: energy self-sufficient building; climate change; different weather conditions; building performance; dynamic simulation; energy optimization.

1. INTRODUCTION

The global energy scenario shows that the building sector is one of the main responsible of energy consumption, accounting for 40% of the total (IEA, 2016), and for 30% of greenhouse gas (GHG) emissions (Zhai and Helman, 2019) which have more than doubled since 1970 (IEA, 2012). This context, associated with increasing global warming, justifies political and research efforts made to limit energy consumption by optimizing the performance of active and passive elements of buildings.

However, the correct combination of Energy Efficiency Measures (EEMs) depends on many factors, including weather conditions that represent the boundary condition that most influences the dynamic behavior of buildings (Chi et al., 2019). Therefore, the effects of EEMs should be assessed according to the climatic condition of the buildings' location, not only in terms of averaged historical weather dataset, but also considering future climate projections generated by shared climate change scenarios. If the buildings' lifespan (usually 50 years) is considered, it is clear that climate change must necessarily be taken into account (Waddicor et al., 2016). In fact, climate change and temperature increase are determining new energy scenarios, redefining the energy performance of buildings and cities (D'Amico et al., 2019). Furthermore, these new scenarios are characterized by an increase in heat waves (both in terms of frequency and duration) and therefore, the influence of heat waves and related mitigation techniques on energy consumption should be investigated (Falasca et al., 2019).

A very popular tool for evaluating weather conditions is climate classification, in particular that of Köppen-Geiger (Peel et al. 2018). This empirical and vegetation-based classification was developed

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by Köppen in the early 1900s and subsequently updated by Geiger. Despite the development of new classification by several authors, the original Köppen-Geiger classification is still the most applied (Kottek et al., 2016).

In this context, the reports and emission scenarios released by the Intergovernmental Panel on Climate Change (IPCC) have a key role. The IPCC was created in 1988 by the World Meteorological Organization and it is the main international body for evaluating climate change. “The IPCC provides regular assessments of the scientific basis of climate change, its impacts and future risks, and options for adaptation and mitigation” (https://www.ipcc.ch/about/). “Future greenhouse gas emissions are the product of very complex dynamic systems, determined by driving forces such as demographic development, socio-economic development, and technological change” (IPCC, 2000). The emission scenarios developed by the IPCC have evolved over the years: the Special Report on Emission Scenarios (SRES) (IPCC, 2000) established four scenario families (i.e. A1, A2, B1, B2) from which six scenario groups derive, three for the A1 family (A1FI, A1B, A1T) and one for the other families. According to the IPCC, the “Special Report on Emissions Scenarios cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments” (IPCC, 2000). Furthermore, they “include the range of emissions of all relevant species of greenhouse gases and sulfur and their driving forces” (IPCC, 2000). The SRES scenarios were used up to the fourth IPCC report, while the Representative Concentration Pathways (RCP) scenarios were used from the fifth IPCC report onwards. This set include four scenarios that “describe four different 21st century pathways of GHG emissions and atmospheric concentrations, air pollutant emissions and land use. The RCPs include a stringent mitigation scenario (RCP2.6), two intermediate scenarios (RCP4.5 and RCP6.0) and one scenario with very high GHG emissions (RCP8.5)” (IPCC, 2014).

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Against this background, it is essential to create scientific interactions between experts from different sectors (i.e. building science and climate science), in order to assess the influence of climate change and to establish appropriate mitigation measures to reduce its effects. Moreover, a detailed prediction of possible future energy scenarios for the building sector would be a great help in implementing appropriate policies and to assess whether current regulations are going in the right direction (da Guarda et al., 2020).

The present work extends a previous paper (de Rubeis et al., 2019) by considering a residential building, located in the outskirt of L'Aquila (Italy), characterized by complete energy self-sufficiency, still uncommon in the European building stock. For the considered building, different energy optimization scenarios have been proposed considering a set of HVAC system solutions, together with different climatic zones (four Italian cities and two European cities) and climate change projections to 2050 and 2080.

On the basis of a calibrated simulation model of the selected building, experimentally analyzed in detail in previous works (de Rubeis et al., 2018, Smarra et al., 2019), the aim of the work is twofold:

- to understand how HVAC system solutions affect the energy performance of the self-sufficient building during the heating season and how optimization margins vary with changing climatic conditions. In this regard, it is worth noting that, although it may be correct to evaluate buildings with different characteristics according to different climatic zones, the choice of evaluating a single building with unchanged properties for different climatic conditions is commonly applied in the literature (see for example Ciancio et al., 2019a; Acione et al., 2016; Troup et al., 2019; Jazaeri et al., 2019; Eicker et al., 2014; Murano et al., 2016). This choice is mainly due by the fact that, by fixing the characteristics of the use case, it is possible to carry

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out a multi-parametric analysis capable of producing disaggregated, comprehensible, comparable and generalizable results.

- based on the climate change projections to 2050 and 2080, to assess the effects of the HVAC system solutions over time, in terms of energy consumption during the heating season.

For the aims of the work, the energy self-sufficiency characteristic of the building, still uncommon in the European building stock, makes the case study particularly interesting to understand possible margins for performance improvement, their effectiveness according to different climate zones and future climate change scenarios.

The paper is divided into 5 sections, as follows: Section 2 presents related works analyzed in literature; Section 3 shows the employed method, the description of the use case and its model, the comparison of weather datasets for different climate zones, and climate change projections. The results are presented and discussed in Section 4. Finally, the main findings of the work are summarized in Section 5.

2. RELATED WORKS

In literature, several studies that analyze the impact of averaged weather data on the buildings' energy performance have been presented (Ciancio et al., 2018; Lupato et al., 2019; Crawley, 1998; Chiesa and Grasso, 2015; Cui et al., 2017). However, the comparison between different climatic zones and the influence of future climate change on real buildings are still poorly studied, especially for the case of an energy self-sufficient building, rather uncommon in the European building stock.

In the work presented by Jazaeri et al. (2019), the combined effects of building characteristics, climate conditions and occupancy patterns are analyzed to evaluate the HVAC demand of a representative residential building. The authors have found that the highest energy reductions are

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obtained in the climates with high diurnal temperature variation by considering representative Australian building and different climates (i.e. tropical, hot, arid, and cold climates).

Eicker et al. (2014) discussed the energy and economic assessment of solar thermal (ST) and photovoltaic (PV) cooling systems for the air conditioning of office buildings. The authors considered three different European cities where to hypothesize an office building with same geometry and dimensions but different profiles and construction. The main findings of the work showed that the PV system determined relative primary energy saving up to 50%, while ST systems up to 37%.

Verichev et al. (2020) presented the analysis of heating energy consumption of residential buildings in three regions in southern Chile by considering future climatic projections based on RCP2.6 and RCP8.5 scenarios provided by IPCC. The authors observed an annual heating energy consumption decrease in a range between 13% and 27% for RCP2.6 and RCP 8.5, respectively.

da Guarda et al. (2020) analyzed the effects of climate change on the energy consumption of a Zero Energy Building (ZEB) located in city of Cuiabá-MT (Brazil), with and without PV system. The main findings of the work highlighted the vulnerability of ZEBs to the impacts of climate change and that the PV plant will not be able to meet the future energy demand from about 14.1% by 2020, 26.3% by 2050, and 40.2% by 2080.

Also Ciancio et al. (2019b) considered the A2 emissions scenario and the future years 2050 e 2080 for their study on the modifications in energy needs for cooling and heating the same residential building located in six different climate Köppen-Geiger classes (19 European cities). In terms of energy demand, their results showed that in 2080 the increase for cooling will be higher than the decrease for heating and that energy needs of northern and central European cities (e.g. Aberdeen or Berlin) will approach those of Mediterranean cities (e.g. Palermo).

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The combination between future climate scenarios and thermal comfort models is proposed by Shen et al. (2020), considering two different European cities and a residential multifamily building. The results showed similar trends for the two cities: from 5.3% to 23.6% of cooling and dehumidification requirements in Rome, from 67% to 53% in Stockholm, and a decrease of heating and humidification needs from 27% to 16% and from 0% to 1.5% in Rome and Stockholm, respectively.

Troup et al. (2019) presented a new approach to determine future climate projections based on fourteen Global Climate Models (GCMs). The future climate scenarios have been tested on a prototypical office building in three different US cities. The results showed a considerable variability depending on the climatic conditions.

The effects of climate change on the Swiss heating and cooling demand of buildings is analyzed by Berger and Worlitschek (2019). The authors have found that, when the RCP8.5 climate scenario is considered, a -40% decrease of heating degree days is observed and a contemporary +1300% increase of cooling degree days by the 2100.

The appropriateness of bioclimatic strategies in relation to future climate change was discussed by Flores-Larsen et al. (2019). The energy performance of a typical Argentinean mid-income residential single-family building is analyzed and the results highlighted that the annual energy use, between the baseline period (1961-1990) and 2080, will decrease in the range from -25% (Córdoba) to -8% (Mendoza), and it will increase by 6% in Orán.

Nematchoua et al. (2019) discussed the effects of climate change on the energy consumption of hospital buildings considering six different cities located in six countries in the Indian Ocean region. Passive and active strategies have been considered and the main findings showed annual energy demand increase between 17.1% – 25.4% by 2030, 34.6% – 50.2% by 2060, and 60.8% – 95.1% by 2090.

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Waddicor et al. (2016) analyzed the energy performance of an Italian library, by considering climate change and ageing factors. The authors noted that when climate change alone is taken into account, there is an increase in cooling energy needs and a reduction in heating energy requirements, and that these changes are accentuated when ageing factors are also considered. Jiang et al. (2019) developed a new web-based *Weather Morph: Climate Change Weather File Generator* useful to create climate projections on the basis of all IPCC emission scenarios, and in three future time horizons (i.e. 2020s, 2050s, and 2080s). Their application allows to obtain climate projections in a dual format TMY (Typical Meteorological Year) and EPW (EnergyPlus Weather), to allow their use with simulation tools.

By considering a campus building stock, Zhai and Helman (2019) discussed 56 models and scenarios of future climate data and the effects on building energy performance. They identified four reference climate models for three time periods and seven climate zones in United States. The main findings revealed cooling energy increases equal to 5%, 28%, 20%, and 52% respectively, for the low, low-mid, mid-high, and high models.

The work presented by Rey-Hernández et al. (2018) discusses how climate change impact on zero energy status of a zero energy and carbon dioxide building located in Valladolid (Spain). They have found a remarkable increase of the cooling demand (from 48% by 2020 to 69% by 2080) and a contemporary reduction of space heating requirements (from 36% by 2020 to 18% by 2080). Gercek and Durmuş Arsan (2019) discussed the relation between design parameters and future climate change for a mid-rise residential building in Izmir (Turkey). The main results of the work highlighted an increase of 29.2% of annual heating consumption by 2080s and 14.0% by 2050s due to the growing cooling demand.

An analysis at housing stock scale is presented by Domínguez-Amarillo et al. (2019) with the aim of assessing the capability of the stock to adapt to future climate scenarios. Considering the city of

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Seville (Spain) as case study, the authors identified six different scenarios for envelope, climate, and temperature set, and assessed that the thermal insulation of the envelope alone does not allow an optimal energy response.

Figueiredo et al. (2020) applied a sensitivity analysis to assess the effects of climate change on the energy performance of the whole Portuguese residential building stock. The results showed an increase from 5% to 60% of the total electricity consumption by 2050, with a reduction of space heating demand by 33% and a significant increase in cooling energy requirements (by 20 times).

An analysis of the effects of climate change on heating and cooling degree day (HDD and CDD) is presented by Ramon et al. (2020). They have found a decrease of HDD with 27% between 1976-2004 and 2070-2098, and an increase of the CDD from 167 to 401 CDD in the same period.

For the sake of comprehensiveness, Table 1 summarizes the main findings of the related works analyzed.

Based on the studies previously examined, it is possible to observe that there are numerous works focusing on the relationship between climate zones, climate change and their effects on buildings energy performance, at various levels of detail (building or building stock scale). However, it can also be noticed that there are still few works that carry out such assessments considering a real building, and, in particular, completely energy self-sufficiency buildings, in spite of European directives tend towards this condition (Rey-Hernández et al., 2018). Therefore, this work mainly aims at assessing the effects of different HVAC solutions on the energy performance of a real and energy self-sufficient building, considering different climate zones in Europe and future climate change scenarios.

Table 1. Summary of studies with different climate zone and climate change impacts on energy consumption.

Authors	Year	Climate zone	Climate change projections approach	Time horizon	Simulation tool	Case study
Verichev et al.	2020	Chile (La Araucania, Los Rios, Los Lagos)	RCP2.6 and RCP8.5 scenarios (IPCC)	2035-2050 and 205-2065	REVIT, GREEN BUILDING STUDIO, ARCGIS, IBM SPSS	Typical Chilean house

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da Guarda et al.	2020	Brazil (Cuiabà-MT)	A2 emission scenario (IPCC)	2020, 2050 and 2080	ENERGYPLUS	Single-family house
Figueiredo et al.	2020	Europe (Portugal)	RCP2.6, RCP4.5, RCP8.5 (IPCC)	2050	-	Whole Portuguese residential building stock
Ramon et al.	2020	Europe (Belgium)	RCP8.5 (IPCC)	2069-2099	-	National level
Ciancio et al.	2019 b	Europe (19 cities)	A2 emission scenario (IPCC)	2050 and 2080	ENERGYPLUS	Residential building
Shen et al.	2020	Europe (Rome and Stockholm)	RCP2.6, RCP4.5, RCP8.5, SRES A1B scenarios (IPCC)	2020, 2050 and 2080	IDA (ICE)	Residential multifamily building
Troup et al.	2019	USA (Boston, Miami, and San Francisco)	RCP4.5 and RCP8.5 (IMPCC)	2030, 2060, and 2090	ENERGYPLUS	Prototypical office building
Berger & Worlitschek	2019	Europe (Switzerland)	RCP2.6, RCP4.5, RCP8.5 (IPCC)	2019, 2050, and 2099	-	National level
Flore-Larsen et al.	2019	Argentina (Santa Rosa, Mendoza, Cordoba, Oràn)	A2 emission scenario (IPCC)	2020, 2050 and 2080	ENERGYPLUS	Residential single-family building
Nematchoua et al.	2019	Indian Ocean region (six cities in six countries)	B1, A1B, and A2 scenarios (IPCC)	2030, 2060, and 2090	ENERGYPLUS	Hospital
Jazaeri et al.	2019	Australia (10 cities)	-	-	TRNSYS	Representative Australian building
Jiang et al.	2019	Beijing, Chicago, Hong Kong, Los Angeles, London, Miami, Rome, Sidney	B1, B2, A2, and A1F1 scenarios (IPCC)	2020, 2050 and 2080	Web-based Weather Morph	-
Zhai and Helman	2019	USA (seven climate zone as defined by ASHRAE)	RCP2.6, RCP4.5, RCP6, and RCP8.5 scenarios (IPCC)	2010-2039, 2040-2069, 2070-2099	ENERGYPLUS	Campus scale
Domínguez-Amarillo et al.	2019	Europe (Spain - Seville)	A2 emission scenario (IPCC)	2050	ENERGYPLUS	Housing stock scale
Gercek & Durmus Arsan	2019	Europe (Turkey - Izmir)	A1, A2, B1, and B2 scenarios	2020, 2050 and 2080	ENERGYPLUS	Mid-rise residential building
Rey-Hernandez et al.	2018	Europe (Spain - Valladolid)	n/a	2020, 2050, and 2080	ENERGYPLUS	Zero Energy and Carbon Dioxide Building
Waddicor et al.	2016	Europe (Italy - Turin)	A2 and B1 scenarios (IPCC)	From 2010 to 2060 with decadal steps	IDA (ICE)	Library
Eicker et al.	2014	Europe (Italy - Palermo, Madrid, Stuttgart)	-	-	TRANSOL EDU 3.0 & INSEL 7.0	Simulated (IEA Task 25)

3. METHOD

A series of experimental tests have been performed in a previous work (de Rubeis et al., 2018), in order to evaluate qualitative aspects of the building, including: infrared thermography technique, heat flow meter method, indoor ambient and surface temperatures, actual energy consumption of

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the heating system by means of a heat meters, and outdoor weather data for the city of L'Aquila. This analysis, has allowed the creation of a simulation model (with EnergyPlus simulation tool), calibrated on the basis of experimental energy consumption data. The calibrated model of the energy self-sufficient building allowed: i) to evaluate the effects of different HVAC system solutions on its heating energy performance; ii) to analyze the impact of the same solutions by considering different weather conditions (i.e. four Italian cities - L'Aquila, Rome, Palermo and Milan - and two European cities, Madrid and London) (de Rubeis et al., 2019); iii) to analyze the building energy performance in heating season taking into account two climate change scenarios (projections to 2050 and 2080). Starting from the "present-day" hourly weather file of the city of L'Aquila, the future weather files (.epw format) have been obtained by using the morphing method. The schematization of the methodology used in this work is shown in Fig. 1.

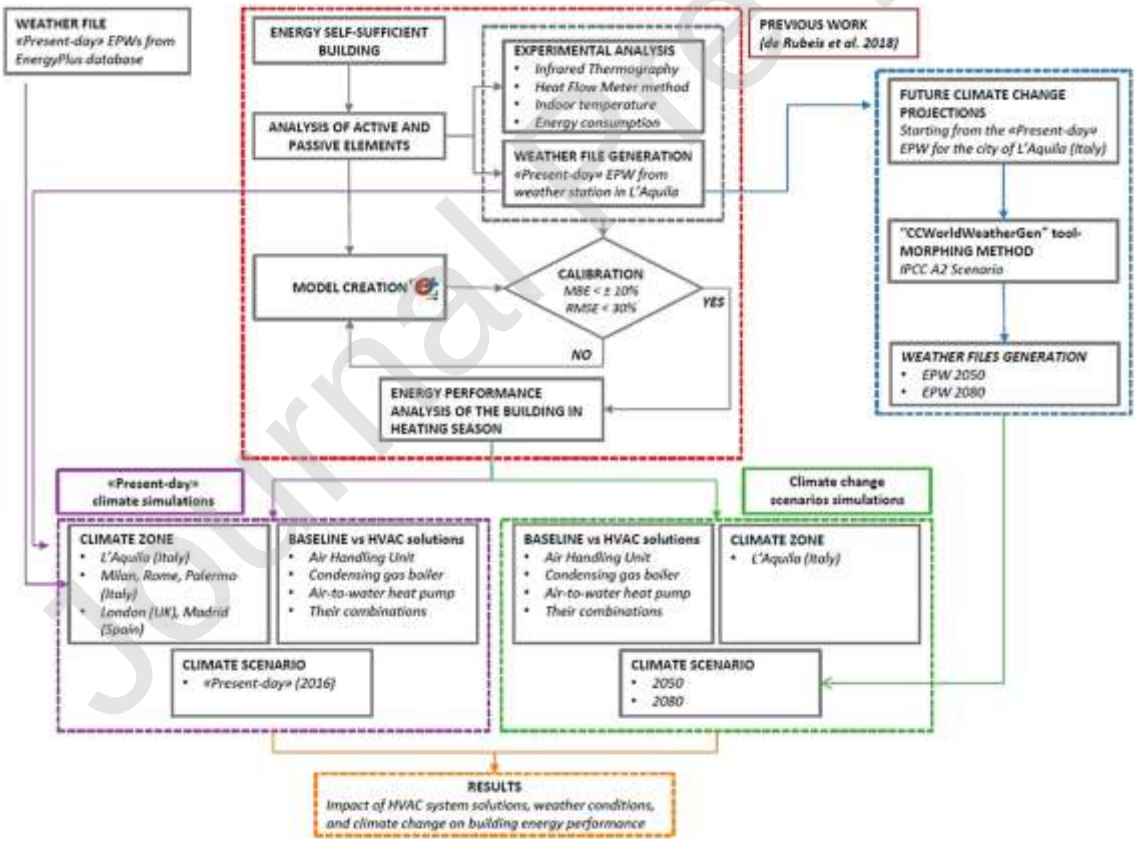

Figure 1. Flowchart of the employed methodology.

3.1. Case study description

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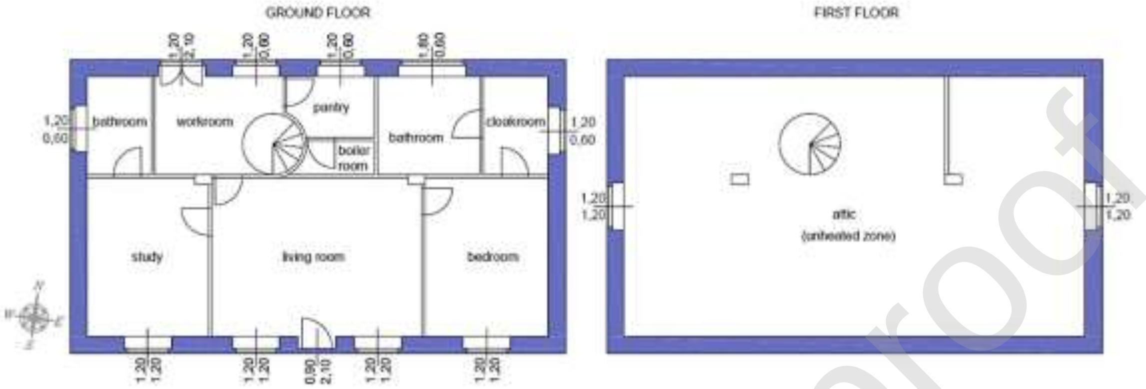
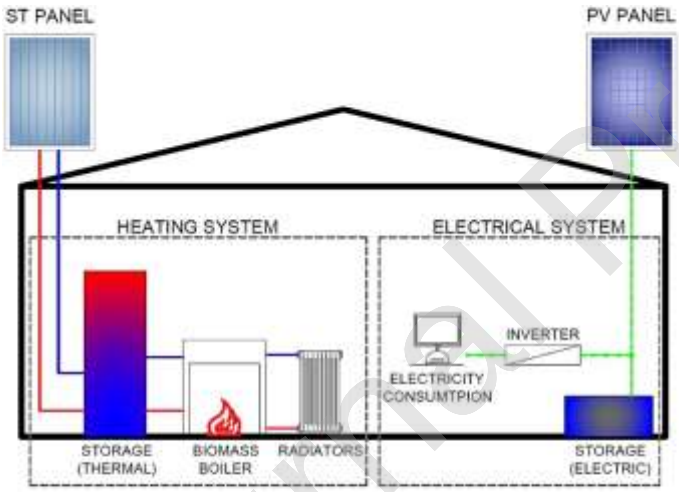
The analyzed building (Fig. 2a) is a two-story residential single-house, full time inhabited by two people, the owners, and located in the outskirts of L'Aquila (lat. 42°21', lon. 13°23'). The building, whose architectural distribution is shown in Fig. 2b, has a reinforced concrete bearing structure with EPS (Expanded Polystyrene) insulation and envelope made of prefabricated wood-cement blocks with high thermal performance, as discussed in Nardi et al. (2016). The thermal transmittance values of walls, floor, roof are equal to 0.12 $Wm^{-2}K^{-1}$, 0.28 $Wm^{-2}K^{-1}$, and 0.13 $Wm^{-2}K^{-1}$, respectively. From the HVAC system point of view, the building has been realized to maximize the use of renewable sources in order to make it totally independent from the utilities. Therefore, following the definition provided by Torcellini et al. (2006), the case study can be considered a Zero Energy Building, being able to produce enough renewable energy in situ to cover its energy needs. This result was achieved thanks to the installation of biomass heat generator (nominal thermal power 16.5 kW, efficiency 83.5%), solar thermal plant with flat collectors, thermal energy storage for Domestic Hot Water (DHW), and stand-alone photovoltaic plant (Fig. 2c). The electricity produced by the PV plant is primarily used by the users of the house (e.g. lighting, cooking, etc.) and secondarily used to recharge the batteries. Being a stand-alone system without connections to the national grid, if excess electricity is produced and not used by the house or batteries, it is lost. The thermal energy produced by the solar thermal system is stored in a tank where an additional heat exchanger allows the integration of thermal energy from the biomass boiler, to ensure the production of DHW. However, both PV plant and ST plant are not discussed in our work. The heating energy needs are satisfied by a hydronic system, where the biomass boiler feeds the radiators and the heating system control strategies are based on a manual switch on/off of the biomass boiler. The heated ground floor of the building includes all the occupied rooms, while the attic is unheated. The natural ventilation guarantees the air changes. Table 2 summarizes the main parameters of the building systems.

(a)



(b)



(c)

Figure 2. The case study. (a) South façade of the energy self-sufficient building. (b) Architectural distribution. (c) Simplified scheme of technological plants.

Table 2. Main parameters of the building systems.

Description	Value	Units
Heated net area	99.1	m^2
Surface to volume ratio	1.03	m^{-1}
Transmittance value (wall)	0.30	W/m^2K
Transmittance value (floor)	0.30	W/m^2K
Transmittance value (roof)	0.25	W/m^2K
Biomass boiler efficiency	83.5	%

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Biomass boiler nominal power	16.5	kW
PV plant typology	Stand-alone	-
PV plant nominal power	8	kW_p
PV plant surface	53	m^2
PV storage system	3x12 batteries (12 V, 100 Ah)	-
ST collector typology	Flat plate	-
ST collector dimension	2.5	m^2
Tank volume	200	l

3.2. Modeling and multi-scenario analysis

The EnergyPlus simulation software, one of the most used for building dynamic simulation (Nguyen et al., 2014), was used to create the model of the energy self-sufficient building (Fig. 3) in which all its characteristics were taken into account (geometry, activity, orientation, air leakages, air changes, internal gains, orientation, and so on). The simulation model was then calibrated by comparing simulation results and actual energy consumption of the heating system, experimentally measured by means of a heat meter, with a sub-hourly trend (10 minutes). The thermal energy employed for DHW is not examined in this work. The experimental data allowed to calibrate the model by means of the statistical approach proposed by the ASHRAE Guidelines (U.S. DOE, 2015) and 4500 samples were used to evaluate two statistical indices, MBE (Mean Bias Error) and CV(RMSE) (Coefficient of Variation of the Root Mean Square Error). At the end of the calibration phase, the two indices resulted equal to 5.31% and 6.95% respectively, both lower than the limits set by ASHRAE for the hourly model calibration (±10% and 30%, respectively). More detailed information about the calibration phase can be found in de Rubeis et al. (2018).

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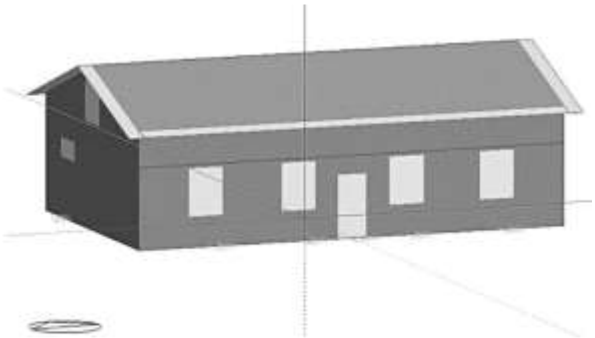

Figure 3. Simulation model of the building.

Therefore, the calibrated model availability allowed to carry out an energy performance analysis of the building in its "baseline scenario", but also examining the effects of various HVAC solutions, all aimed at assessing the performance of the heating system. Hence, five possible interventions have been hypothesized, synthetically shown in Table 3.

Table 3. Optimization scenarios hypothesized for energy evaluation.

Scenarios	Biomass boiler	Condensing gas boiler	Air-to-water heat pump	Air handling unit
OS-1	✓			✓
OS-2		✓		
OS-3		✓		✓
OS-4			✓	
OS-5			✓	✓

3.3. Climate zones

The building energy performance is strongly influenced by weather conditions and, therefore, the quantification of their impact is very useful to compare the effects of different HVAC solutions. In the literature, although with different purposes, some studies consider the effectiveness of optimization interventions according to different weather conditions, assuming to locate the same building in different climate zones (Eicker et al, 2014; Jazaeri et al., 2019; Shen et al., 2020; Troup et al., 2019; Flores-Larsen et al., 2019; Murano et al., 2016).

In this work, the evaluation of the effects of HAVC solutions described in Table 3 is conducted considering the different weather conditions that characterize four Italian cities (L'Aquila, Rome,

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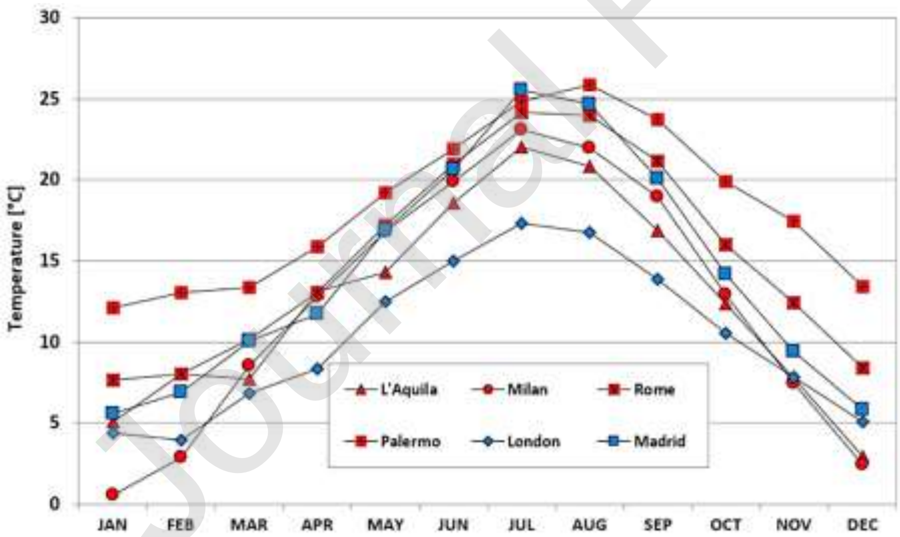
Palermo and Milan) and two European cities (Madrid and London) in the frame of the "present-day" climate, as shown in Fig. 4.

Figure 4. The different European cities considered in this work.

According to the Italian climate classification (D.P.R. n. 412, 1993) the four selected cities are: Palermo, climate zone "B"; Rome, climate zone "D"; Milan and L'Aquila, climate zone "E", while the European cities (Madrid and London) were selected based on the Köppen-Geiger classification (Peel et al., 2018). This classification groups climates into five families, marked by the first letters of the alphabet. Two of these families (i.e. E and B) are characterized by adverse conditions for the growth of the vegetation: the family of polar and high mountain climates (E) and the family of dry climates (B). The other three families (A, C and D) are distinguished by the conditions for growth of trees: the tropical climate family (A) and the rainy temperate family (C and D). These families have further subdivisions within them, which include eleven main types and secondary types and subtypes. According to this classification, Europe has a dominant cold climate D (44.4%), followed by arid B (36.3%), temperate C (17.0%) and polar E (2.3%) climates. Spain has a rather variable climate, mainly BSk, Csa, Csb and Cfb, i.e. mainly arid-steppe and temperate-mild. Madrid, in particular, is characterized by temperate climate with dry summer (Csa, Csb). The United Kingdom (i.e. London) has a very uniform and temperate climate with warm summer (Cfb).

Fig. 5 shows mean temperatures, global solar radiations and wind speeds for the selected cities, derived from the EnergyPlus database (https://energyplus.net/weather), except for the city of L'Aquila, whose weather conditions were directly measured by the weather station owned by CETEMPS - Center of Excellence (http://cetemps.aquila.infn.it/) during the whole year 2016. Figs. 5a and 5b show that the monthly means of temperature and solar radiation have the typical trend during the year, with the highest values in the summer months (June, July, August, September) without significant differences between the cities considered.



(a)

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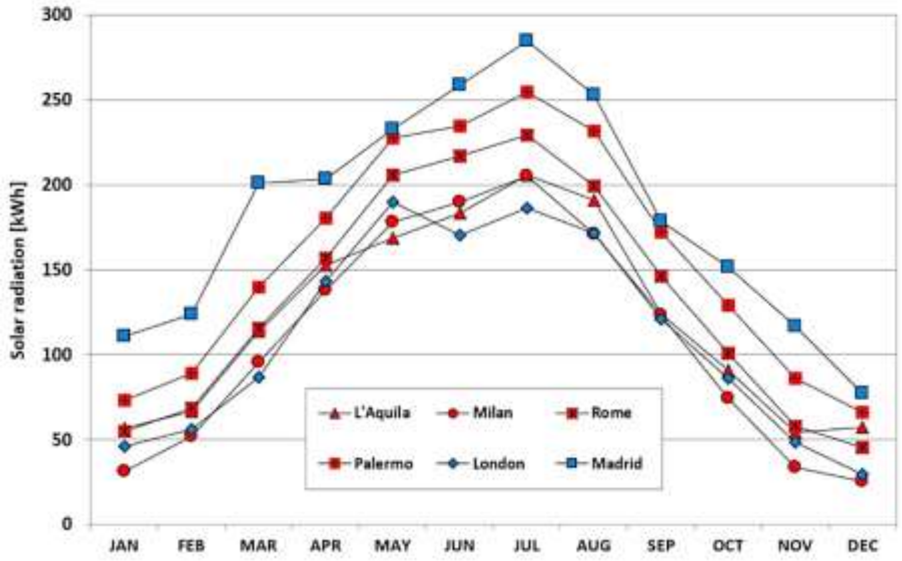

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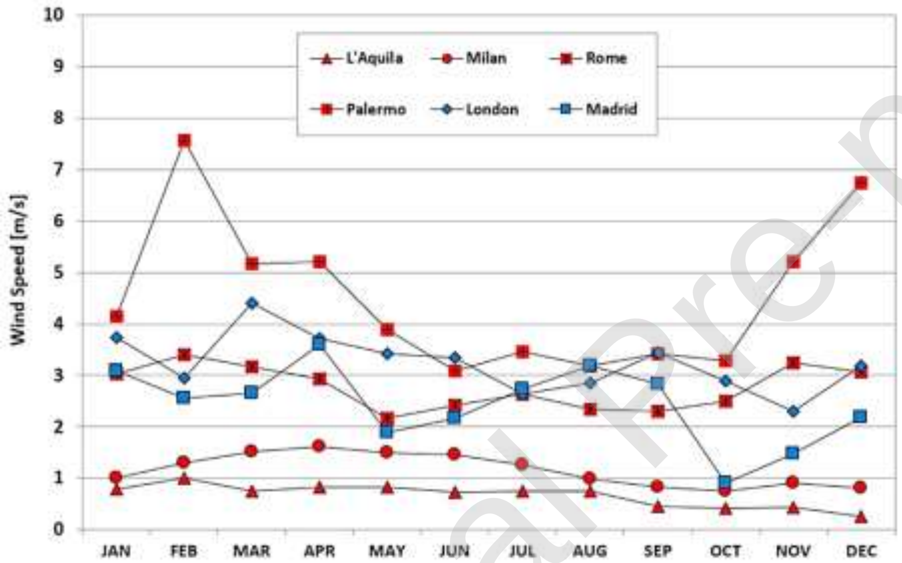

(c)

Figure 5. Weather parameters of the selected cities during the year. (a) Mean dry bulb temperatures. (b) Mean global solar radiation (c) Mean wind speed.

Mean weather conditions of the selected cities during the heating season are reported in Table 4. It is worth noting that, in order to standardize the energy performance analyses, the same heating season has been set for all the cities considered (i.e. 15th October – 15th April). For each parameter (mean temperature, mean solar radiation and mean wind speed) the percentage difference, with respect to L'Aquila, is also given.

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Table 4. Weather conditions for the selected cities during the heating season.

	Köppen–Geiger climate class	Italian Climate Classification	Mean temperature [°C] [a]	Δ% [b]	Mean solar radiation [kWh]	Δ% [b]	Mean wind speed [m/s]	Δ% [b]
L'Aquila (Ref. Case)	Cfb	E	8.1	0.0%	84.6	0.0%	0.6	0.0%
Milan	Cfa	E	6.8	-16.6%	64.3	-24.0%	1.1	75.8%
Rome	Csa	D	10.8	32.7%	85.7	1.3%	3.1	376.8%
Palermo	Csa	B	15.0	84.4%	109.1	29.0%	5.3	733.4%
London	Cfb	N.A.	6.7	-17.6%	70.9	-16.1%	3.3	417.4%
Madrid	Csa	N.A.	9.1	11.6%	140.6	66.3%	2.3	267.1%

[a] Average values during the heating season.

[b] Percentage variations with respect to the reference case, i.e. L'Aquila.

As for the values during the heating season, Table 4 shows that Milan and London have very similar mean temperatures, which are the lowest among the cities considered. L'Aquila, which belongs to the Italian climate class "E" as Milan, is characterized by a mean temperature about 17% higher than that in Milan. Madrid, Rome and Palermo belong to the Csa climate class and have higher temperatures than L'Aquila, respectively of about 12%, 33% and 84%. L'Aquila is located on the Apennines, at just over 700 m above sea level and it is characterized by an average solar radiation of about 85 kWh like Rome. Milan, located in the Po valley and notoriously characterized by phenomena of fog and air pollution, has the lowest average solar radiation among the cities considered (24% less than that of L'Aquila). Madrid and Palermo have the highest average solar radiation, equal to 109 kWh and 141 kWh respectively (29% and 66% more than L'Aquila). L'Aquila is the least windy city among those considered, with an average wind speed of 0.6 m/s, while Palermo is the most windy city with an average wind speed of 5.3 m/s (733% higher than L'Aquila). Rome and London have similar mean wind speeds equal to about 3 m/s. Furthermore, Milan and L'Aquila are characterized by a low oscillation of the monthly mean speed during the year, unlike Madrid, Rome and Palermo where the monthly averages vary significantly during the year (Fig. 5c). The remarkable excursions in Palermo are most likely due to its coastal position.

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3.4. Climate change projections

In order to take climate change for the next decades into account (in the city of L'Aquila), input weather files have been produced for the EnergyPlus software by means of the Climate Change World Weather file Generator "CCWorldWeatherGen", (Jentsch et al., 2008; Jentsch et al., 2013) for the years 2050 and 2080. This tool is based on Microsoft® Excel and generates hourly climate change adapted weather data for locations all over the world, given the following inputs: i) “present-day” weather files in the standard Energy Plus format (.epw); ii) climate change scenario data. In particular, this tool uses the output of experiments performed with the Hadley Center Climate Model (version 3, HadCM3) developed at Met Office that contributed to the Third, Fourth and partly to the Fifth Assessment Report of the IPCC. This model has a spatial resolution of 2.5° x 3.75°, that is about 417 km x 278 km (295 x 278km at 45° North and South) and provides the following weather variables: temperature (°C), maximum and minimum temperature (°C), total incident solar radiation (W/m^2), total downward surface shortwave flux (W/m^2), total cloud in long-wave radiation (fraction), total precipitation change (%), relative humidity (fraction), mean sea level pressure (hPa), wind speed change (%).

The data used concern the A2 scenario family which “describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented and per capita economic growth and technological change are more fragmented and slower than in other storylines” (IPCC, 2000). Although the A2 family of scenarios is now dated, it is still one of the most used scenarios among the studies in this research area (Verichev et al., 2020).

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3.5. The “morphing” method

The approach used to convert the hourly values of the "present-day" weather file into "climate change" weather file follows the morphing method, originally developed by (Belcher et al., 2005) and applied to the UK case by Jentsch et al. (2008), and described in detail in (Jentsch, 2012).

In this context, ‘morphing’ means obtaining “climate anomaly projections to calculate new weather data files for building energy simulations” (Troup and Fannon, 2016). The "morphing" methodology can be considered a spatial and temporal downscaling consisting in adjusting data observed at weather stations based on data provided by global circulation models and regional climate models.

Specifically, in the morphing algorithm the concept of “baseline climate” is fundamental. The “baseline” represents the average of the present-day weather sequence over a number of years and in this case, it is made up of the monthly mean of a given present-day weather variable.

For each month, the application of the morphing algorithm includes the following steps: i) a monthly shift from the baseline, equal to the absolute change in the monthly mean of the considered variable, ii) a monthly stretch, using the fractional change in the monthly-mean value, iii) a combination of the previous two steps. An extensive description of the morphing procedure can be found in Belcher et al., 2005.

Compared to other methods (dynamic downscaling, stochastic weather generation, interpolation), the advantages of this techniques are: the reliability of the “baseline climate”, the consistence of the resulting weather sequence, the use of observed weather data acquired at a real location.

According to Jentsch et al. (2013), the application of this technique has the advantage of being a practical method that requires low calculation resources. Its limitations lie in the uncertainties of the input data (in this case, the output of the HadCM3 model) and in the generation methodology itself (Jentsch et al., 2013). The "morphing approach" has recently been applied in several

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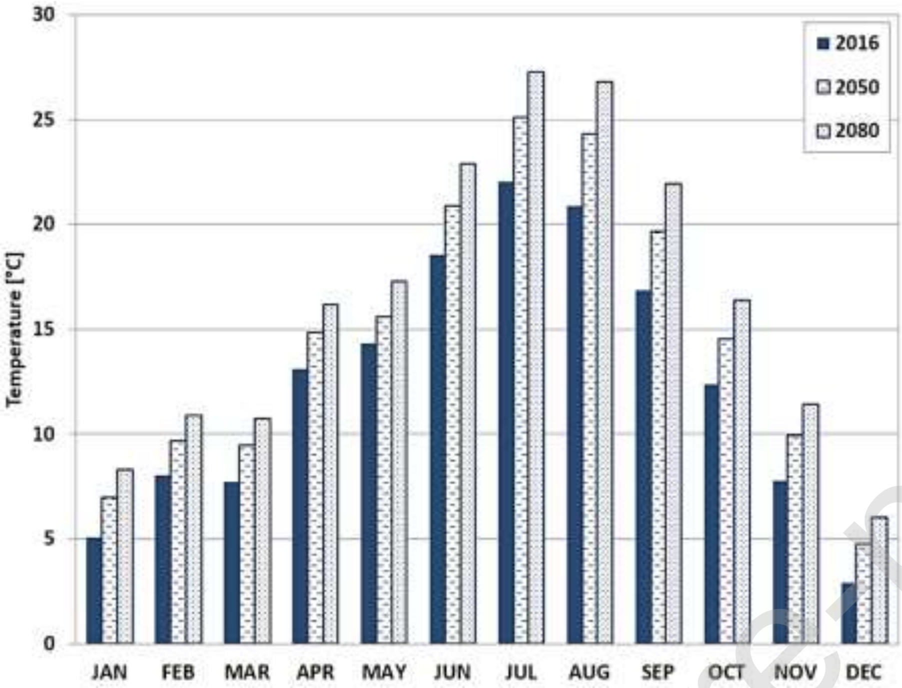
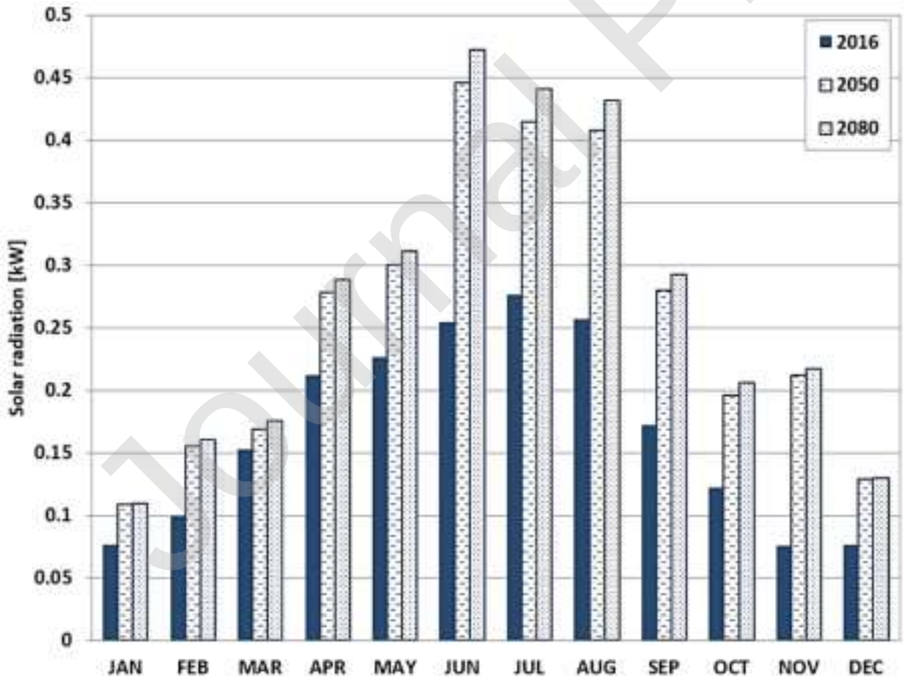
worldwide researches focusing on the impact of climate change on energy needs of buildings (e.g., Wang et al., 2010; Wang et al., 2017; Cellura et al., 2018; Berardi and Jafarpur, 2020).

In this work, the morphing procedure has been applied though the CCWorldWeatherGen tool using the HadCM3 A2 scenario data (both described in section 3.4). First of all, this procedure requires the selection of the “present-day” EPW file for the chosen city and the corresponding weather station (in this case the city of L’Aquila and the CETEMPS weather station), including basic information on the weather station. This information, such as name and geographical coordinates, are needed by the tool in order to find out the four points of the HadCM3 grid closest to the weather station. After the selection of the scenario timeframe (2020, 2050, 2080 are the options) and the loading of the data, the “present-day” EPW file is “morphed” by the tool and the climate change EPW is created. All these points are detailed in the reference manual of the tool (Jentsch, 2012).

Similarly to Section 3.3, where Fig. 5 shows the monthly mean values of the weather parameters pertinent to the “present-day” climate for the six cities considered, Fig. 6 shows the monthly mean values of dry bulb temperature, global solar radiation and wind speed for the three climate scenarios considered, that are the “present day” climate (year 2016) and the two climate projections (years 2050 and 2080). In Fig. 6a, the temperature difference between the future years and the present is greater than zero and essentially constant throughout the year. Furthermore, it is equally distributed between the time slots 2016-2050 and 2050-2080. On the contrary, for the global radiation (Fig. 6b) the differences between the future climate and the “present-day” climate are very dissimilar among the months of the year, although always positive as temperature. For example, in the early months of the year (January, February, March) this difference is much smaller than in the summer months (June, July, August). Furthermore, the 2016-2050 difference is typically slightly higher than the 2050-2080 difference, especially during the summer. As for the wind speed (Fig. 6c), the difference between the monthly mean values in 2016, 2050 and 2080 is practically negligible. In July it is positive and equal to a few decimal points, while in January, February, and March it is negative.



(a)



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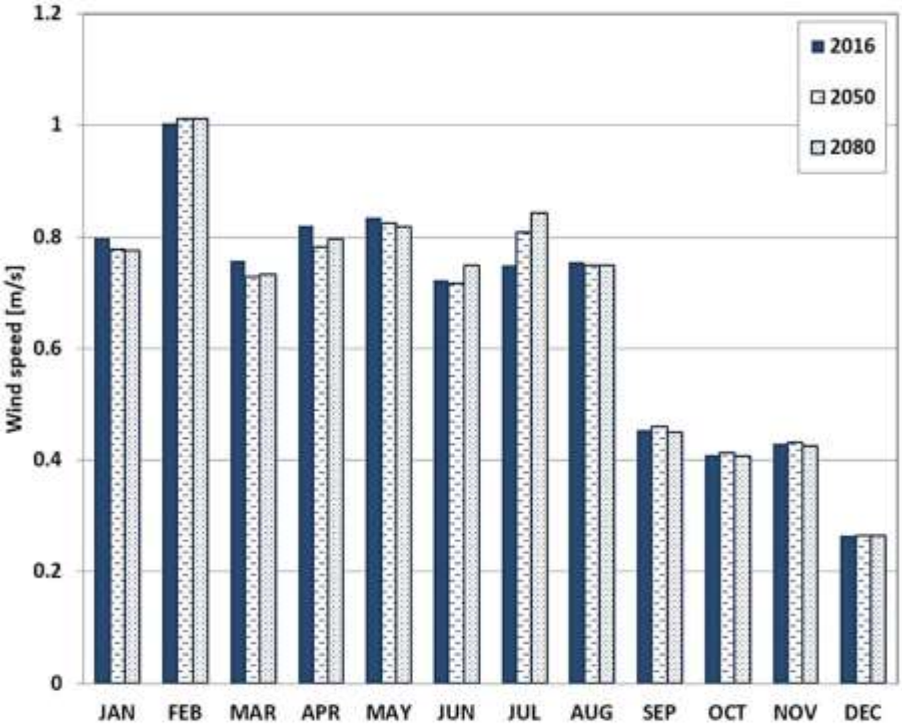

(c)

Figure 6. Weather parameters for L'Aquila during the years 2016, 2050 and 2080. (a) Mean dry bulb temperature. (b) Mean global radiation (c) Mean wind speed.

The characteristic average values of the heating season are shown in Table 5, together with the percentage changes compared to 2016. As discussed about Fig. 6a for the temperature, the percentage change 2016-2080 is approximately twice that of 2016-2050. For solar radiation and wind speed the difference between the average values of the heating season 2050 and 2080 is practically negligible.

Table 5. Weather conditions for the city of L'Aquila during the heating season in the years 2016, 2050 and 2080.

	Mean temperature [°C] [a]	Δ% [b]	Mean solar radiation [kW]	Δ% [b]	Mean wind speed [m/s]	Δ% [b]
2016	7.51	0.0%	0.12	0.0%	0.63	0.0%
2050	9.38	24.9%	0.17	41.6%	0.62	-1.58%
2080	10.75	43.14%	0.17	41.6%	0.63	0.0%

[a] Average values during the heating season.

[b] Percentage variations with respect to 2016, i.e. "present-day" climate.

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4. RESULTS and DISCUSSION

The building characteristics, described in Section 3.1, showed high performance of the envelope, with low thermal transmittance values (between 0.12 and 0.28 $Wm^{-2}K^{-1}$) but low efficiency of the heat generator (83.5%). This assessment was further verified by the numerical modelling, which showed that, for the baseline scenario in L'Aquila, the annual energy consumption per square meter of net living space resulted equal to 29.9 $kWhm^{-2}yr^{-1}$ (and 2964.4 $kWhyr^{-1}$ for the entire heating season), obtained also considering the auxiliaries' consumption. It is worth noting that the energy consumption refers exclusively to heating system without considering other forms of energy (e.g. cooling and domestic hot water). The comparison of this value with the limit values generally imposed for energy-efficient buildings, as for example the limit value of Passive House space heating demand of 15 $kWhm^{-2}yr^{-1}$ (https://passivehouse.com/02_informations/02_passive-house-requirements/02_passive-house-requirements.htm), shows that the energy performance of the use case can be optimized, especially with regard to the heating system. Therefore, the HVAC system solutions proposed in Table 3 are considered also taking into account the different weather conditions, i.e. the different cities described in Section 3.3. The simulation results are summarized in Table 6.

Table 6. Yearly heating energy consumption per square meter of net living space [$kWhm^{-2}yr^{-1}$] and percentage variation.

	Baseline	Δ%[a]	OS-1	Δ%[b]	OS-2	Δ%[b]	OS-3	Δ%[b]	OS-4	Δ%[b]	OS-5	Δ%[b]
L'Aquila	29.9	0.0	**14.0**	**-53.0**	21.0	**-29.7**	**9.8**	**-67.1**	44.4	48.5	17.8	**-40.4**
Milan	32.5	8.8	19.8	**-39.0**	22.8	**-29.8**	**14.0**	**-57.0**	54.2	66.7	24.0	**-26.3**
Rome	29.2	**-2.5**	**10.7**	**-63.2**	20.5	**-29.8**	**7.5**	**-74.2**	32.4	11.1	**12.7**	**-56.3**
Palermo	18.2	**-39.0**	**4.2**	**-77.1**	**12.6**	**-30.7**	**3.0**	**-83.7**	**14.4**	**-21.2**	**4.5**	**-75.1**
London	34.9	16.5	18.7	**-46.3**	24.6	**-29.6**	**13.1**	**-62.4**	50.5	45.0	21.5	**-38.4**
Madrid	33.9	**-10.6**	18.3	**-67.4**	23.8	**-29.7**	**12.8**	**-77.1**	50.8	31.0	22.1	**-50.7**

[a] Percentage variation with respect to reference state in original location (L'Aquila).

[b] Percentage variation with respect to baseline scenario in each city.

Scenarios with reduced energy consumption are shown in bold and values below 15 $kWhm^{-2}yr^{-1}$ are in green.

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For the different weather conditions, the baseline scenario shows that the cities characterized by a colder climate with a higher outdoor thermal forcing have energy consumption partially mitigated by the good thermophysical properties of the building envelope. In this sense Milan and London, with average outdoor temperatures respectively 16.6% and 17.6% lower than L'Aquila, show increases of energy consumption not proportional to these values, and equal to 8.8% and 16.5%, respectively. The same behavior, but reversed, can be seen for the cities with milder climates, i.e. Palermo, Madrid and Rome, which, although characterized by higher average outdoor temperatures than L'Aquila (84.4%, 11.6% and 32.7%, respectively), show attenuated energy consumption reductions (equal to 39.0%, 10.6% and 2.5%, respectively).

The installation of Air Handling Unit (AHU) with heat recovery (OS-1 scenario) shows significant energy benefits particularly for the cities characterized by warmer climate. In fact, considering the percentage variation with respect to the baseline scenario, the best energy performance is obtained for Palermo (-77.1% of energy consumption), followed by Madrid (-67.4%) and Rome (-63.2%). This result is mainly to the efficiency of the AHU's heat exchanger (equal to 80%) which, for cities with a milder climate, treats warmer outdoor air.

The OS-2 solution, characterized by the replacement of the biomass heat generator with a more efficient condensing gas boiler (efficiency 98.0%), determines energy savings almost equal for all the climate conditions considered, and approximately equal to 30.0%. This effect is due to the increased efficiency of the heat generator, which is completely independent from climatic conditions.

The hypothesis of installing an Air-to-Water Heat Pump (AWHP) replacing the biomass boiler (OS-4 scenario) determines negative effects for all the considered cities, except for Palermo, for which an energy saving of 21.2% is obtained. For all other cities, the installation of AWHP has negative energy consumption effects, which increase where weather conditions are more severe (e.g. an

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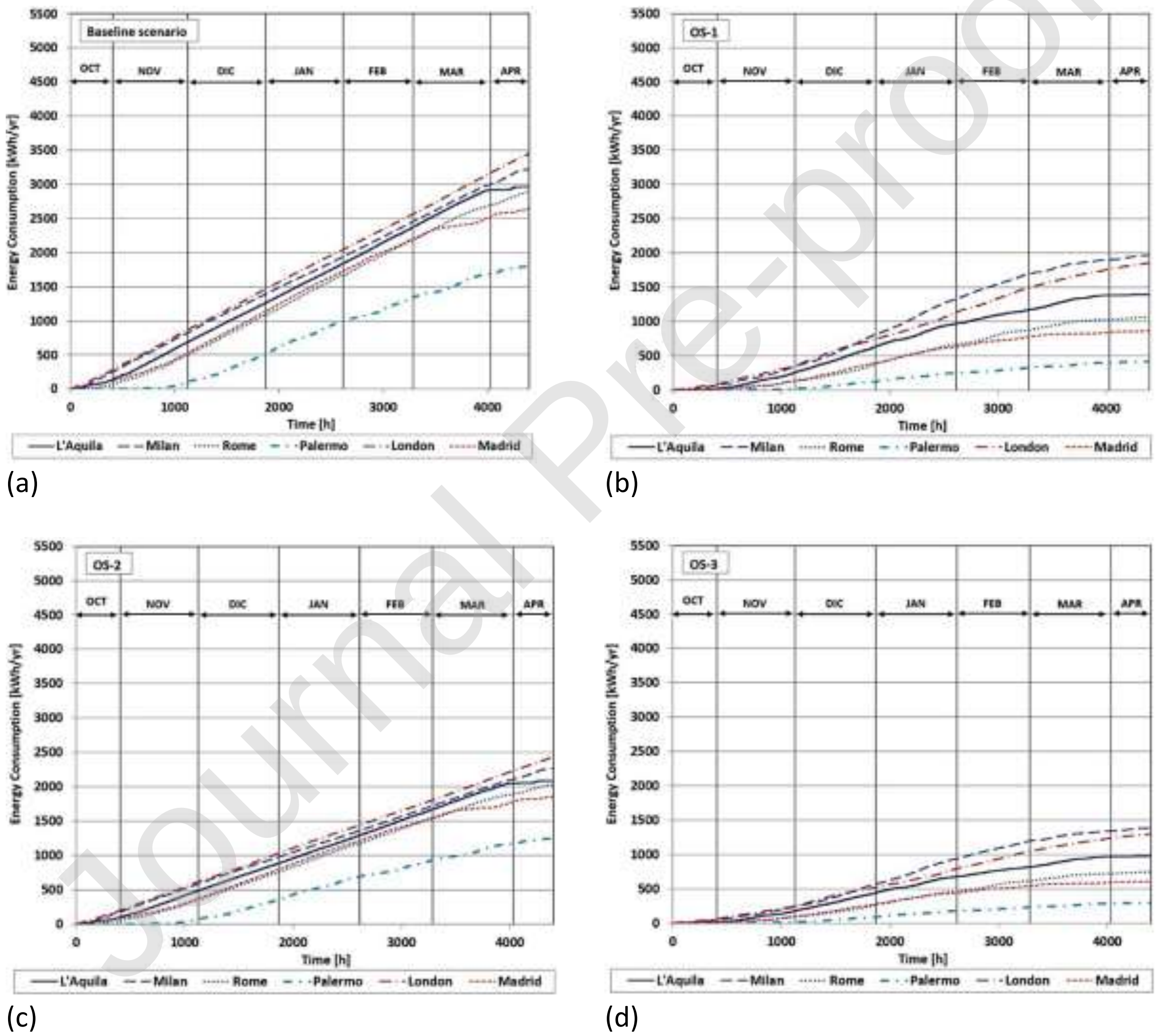
increase of 66.7% is obtained for Milan). The negative performance of AWHP is mainly due to the low outdoor temperatures and the simultaneous high relative humidity values that negatively affect the COP (Coefficient of Performance) of the heat pump (equal to 3.7).

The installation of AWHP becomes energetically feasible if accompanied by AHU (OS-5 solution) thanks to a reduction in heat demand.

Energy consumption trends of the heating system for all HVAC system solutions and climatic conditions are shown in Fig. 7.



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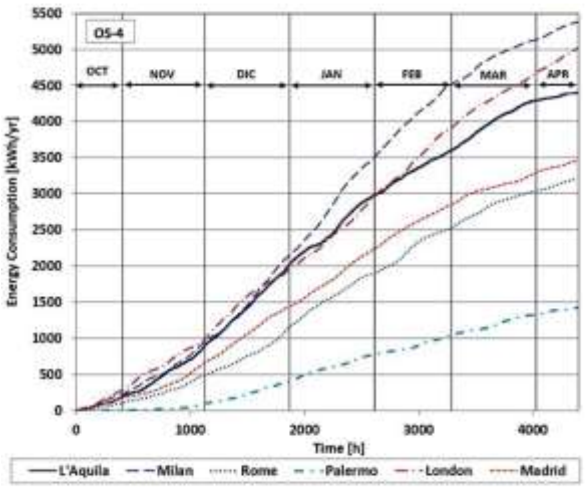

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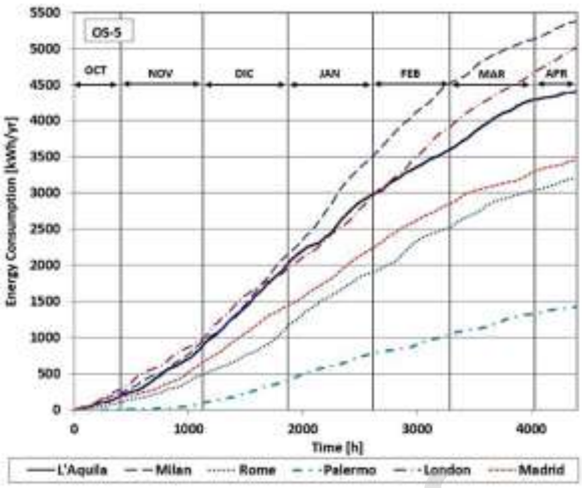

(f)

Figure 7. Main results of the multi-scenario analysis in different weather conditions. (a) Baseline scenario. (b)-(f) Different scenarios (please ref. to Table 3).

The energy performance variability of the scenarios during the heating season can be seen in Fig. 7 through the different slopes of the curves. Moreover, the plotted curves show two different trends depending on whether the machines hypothesized are dependent on weather conditions or not. In particular, Figs. 7a and 7c show rather constant linear trends since these solutions involve the use of machines (i.e. biomass boiler and condensing gas boiler) whose operation is independent of climatic conditions and is exclusively function of their efficiency. Differently, all the cases in which the installation of AHU and AWHP is foreseen, whose operation is strictly related to outdoor climatic conditions, show more variable trends during the heating season. In fact, without considering the city of Palermo, the only one that benefits from the installation of AWHP (-21.2% of energy consumption), the OS-4 scenario appears to be the most affected by outdoor weather conditions, showing a significant difference in energy consumption. Taking the two most distant cases into account, Milan (54.2 $kWhm^{-2}yr^{-1}$, +66.7%) and Rome (32.4 $kWhm^{-2}yr^{-1}$, +11.1%), a significant difference of 40.2% (21.8 $kWhm^{-2}yr^{-1}$) is observed.

When the climatic projections to 2050 and 2080 for the city of L'Aquila are considered, very interesting results are obtained for all the considered HVAC system solutions (see Table 7).

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In general, similarly to what is already discussed in other works (Verichev et al., 2020; Huang and Gurney, 2016; Shen et al., 2020; Berger and Worlitschek, 2019; Invidiata and Ghisi, 2016, Hosseini et al., 2018), heating energy consumption tends to decrease over the years. This reduction ranges from a minimum of 8.5% (for the baseline scenario in 2050) to a maximum of 44.8% for the OS-5 scenario evaluated in 2080. Therefore, it is interesting to observe how climate projections substantially modify the energy results obtained for the "present-day" making the OS-5 scenario very competitive from an energy point of view. Among all the considered cases, the best energy performance is still obtained with the OS-3 scenario (combination of condensing gas boiler and AHU) with annual energy consumption of 6.6 $kWhm^{-2}yr^{-1}$ (in 2050) and 5.3 $kWhm^{-2}yr^{-1}$ (in 2080). Moreover, as previously observed in the case of the different weather conditions (Table 6), even considering future climate projections, the scenarios where the interventions involve machines that operate totally independently of the climatic conditions are less subject to energy benefits. In fact, both the baseline and OS-2 scenarios have energy consumption reductions of 8.5% in 2050 and 17.5% in 2080.

Table 7. Energy consumption results (in $kWhm^{-2}yr^{-1}$) by comparing "present-day" and climate change projections for the city of L'Aquila.

	Baseline	Δ%[a]	OS-1	Δ%[a]	OS-2	Δ%[a]	OS-3	Δ%[a]	OS-4	Δ%[a]	OS-5	Δ%[a]
2016	29.9	0.0	**13.5**	0.0	21.0	0.0	**9.3**	0.0	44.3	0.0	17.8	0.0
2050	**27.3**	**-8.5**	**9.7**	-28.5	19.2	-8.6	**6.6**	-28.6	34.2	-22.8	**12.1**	-31.8
2080	24.6	-17.5	**7.8**	-42.4	17.3	-17.7	**5.3**	-42.5	28.6	-35.4	**9.8**	**-44.8**

[a] Percentage variation with respect to "present-day" (2016).
The lower variation compared to the "present-day" is highlighted in red, while the higher in blue. Values below 15 $kWhm^{-2}yr^{-1}$ are in green.

The energy consumption trends for the different HVAC solutions and climate projections are shown in Fig. 8. Although characterized by different slopes of the curves (determined by the heat generators' efficiencies), it is worth noting that the baseline and OS-2 scenarios display a more progressive decrease in energy demand from present to future scenarios, while the others display

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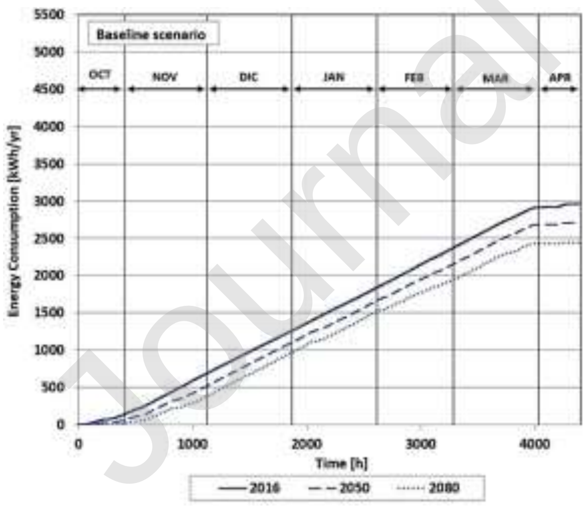
a larger difference for 2016-2050 than for 2050-2080. Baseline and OS-2 show similar decreases in the periods 2016-2050 (-8.5% and -8.6%, respectively) and 2016-2080 (-17.5% and -17.7%, respectively). Moreover, the same two solutions show a greater energy consumption reduction in the period 2050-2080 than in 2016-2050, while all other cases (OS-1, OS-3, OS-4, and OS-5) show the opposite behavior. Some energy management strategies may thus imply a more “prompt” response to climate change (OS-1, OS-3, OS-4, OS-5), but at the same time may tend to “saturate” their beneficial effects in the long term, because the benefit in the period 2050-2080 is diminished with respect to 2016-2050.

All the scenarios show initial (October) and final (April) trends characterized by lower curve slopes, which sometimes appear to be horizontal and asymptotic. This behavior is more evident in the cases where the installation of the AHU is hypothesized, as its installation determines an energy advantage in the intermediate seasons due to the lower operation of the heat generator.

Largest differences are again found in OS-4 intervention, which is however generally pejorative with respect to the baseline energy management configuration.



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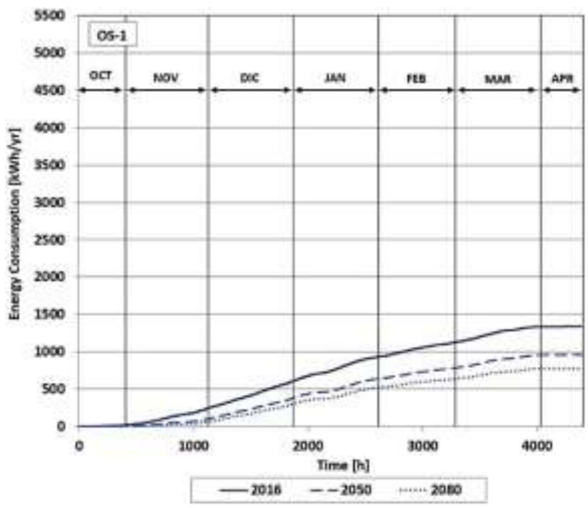

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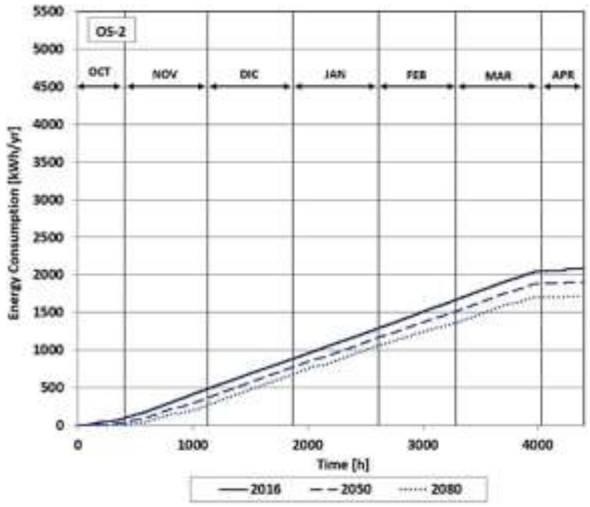

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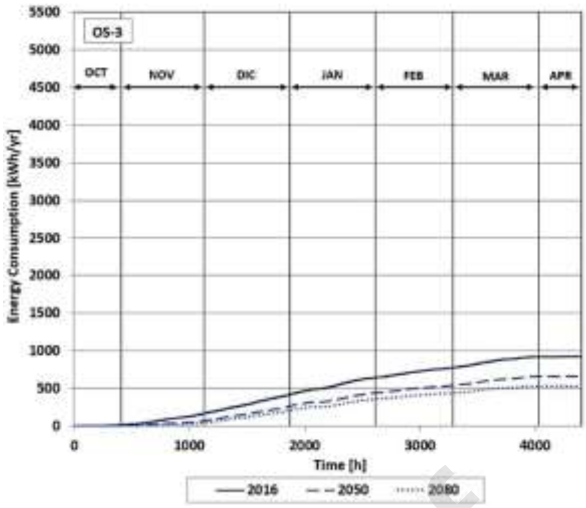

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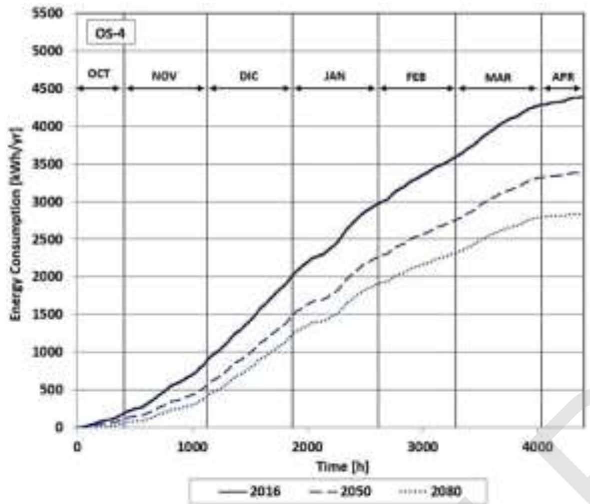

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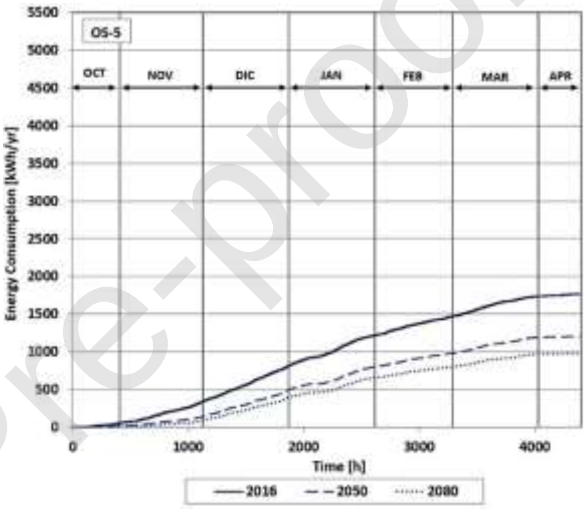

(f)

Figure 8. Main results of the comparison between energy consumption for the "present-day" (2016) and the climate change projections (2050 and 2080). (a) Baseline scenario. (b)-(f) Different scenarios (please ref. to Table 3).

Considering the significant energy savings achieved with some of the scenarios discussed and assessing the effects of climate change, it is interesting to carry out a simplified techno-economic analysis. Clearly, being the case study completely self-sufficient and obtaining the fuel (i.e. vegetable biomass) from the nearby forest, it has no energy costs (complete energy self-sufficiency - first line in Table 8). However, assuming that the fuel is purchased, it is worth analyzing the economic effects of different scenarios and climate change for the city of L'Aquila. The analysis, previously presented in de Rubeis et al. (2018), is expanded here by analyzing the

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effects of climate change on a simplified indicator, such as the Simple Payback Period (SPP), defined by Eq. (1):

$$SPP = \frac{I_n}{e_{savings} - m_{cost}} \tag{8}$$

where (I_n) is the initial cost [€], ($e_{savings}$) is the energy savings [€/y], and (m_{cost}) is the maintenance cost [€/y]. The results of the techno-economic analysis are summarized in Table 8.

Table 8. Simple Pay Back analysis by comparing different scenarios and future climate change for the city of L'Aquila.

Scenario	(I_n) [€][a]	E_c [kWh/yr]	E_{cost}[b] [€/yr]	e_{save} [€/yr]	SPP[c] [yr]	E_c [kWh/yr]	E_{cost}[b] [€/yr]	e_{save} [€/yr]	SPP[c] [yr]	E_c [kWh/yr]	E_{cost}[b] [€/yr]	e_{save} [€/yr]	SPP[c] [yr]
		2016				2050				2080			
Self-suff.	1729.2	2964.5	0.0	0.0	-	2705.4	0.0	0.0	-	2437.9	0.0	0.0	-
Orig. state	1729.2	2964.5	183.8	0.0	-	2705.4	167.7	0.0	-	2437.9	151.1	0.0	-
OS-1	1697.0	1392.1	86.6	97.2	21.2	961.3	65.2	102.5	19.8	773.0	53.5	97.6	21.0
OS-2	1409.5	2084.4	89.4	94.4	17.6	1902.7	81.6	86.1	19.6	1714.4	73.5	77.6	22.2
OS-3	3106.5	974.7	49.1	134.7	30.0	654.1	37.6	130.1	31.4	525.2	32.1	119.0	35.3
OS-4	7833.6	4401.4	792.3	-608.5	NP*	3389.2	610.1	-442.3	NP*	2834.3	510.2	-359.0	NP*
OS-5	9530.6	1767.5	318.2	-134.4	NP*	1199.1	215.8	-48.1	NP*	971.2	174.8	-23.7	NP*

[a] These values are obtained from the official price list of the Abruzzo region (http://www.regione.abruzzo.it/osservatorioappalti/prezzario/).
[b] Although the energy prices are subject to future modification, the energy costs are based on the following energy prices: electric power: 0.18 €/kWh, natural gas: 0.0429 €/kWh, vegetable biomass: 0.062 €/kWh (http://ec.europa.eu/eurostat/data/database). The urbanization costs are neglected.
[c] The maintenance cost was assumed equal to 0.5% of the initial cost.
*NP: not profitable.

5. CONCLUSIONS

In this work, the sensitivity of heating energy performance of a real-world energy self-sufficient building located in L'Aquila (Italy) is analyzed in relation to different climate zones, resulting from four Italian and two European cities, and future climate change projections to 2050 and 2080.

The energy demand of the building during the heating season is analyzed by means of a calibrated EnergyPlus simulation model. Five different HVAC system solutions are considered including Air Handling Unit, condensing gas boiler, Air-to-Water Heat Pump, and their combination.

The main findings of the work showed that:

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- the cities characterized by a colder climate with a higher outdoor thermal forcing have energy consumption partially mitigated by the good thermophysical properties of the building envelope;
- the Air Handling Unit brings significant energy benefits especially for cities characterized by a milder climate (Palermo -77.1%, Madrid -67.4% and Rome -63.2%);
- except for the city of Palermo, the installation of Air-to-Water Heat Pump has shown a considerable dependence on outdoor weather conditions, resulting in energy consumption increase for all weather datasets between 11.1% (Rome) and 66.7% (Milan);
- thanks to future climate projections, a decrease in energy consumption was observed in a range between -8.5% (for the baseline scenario in 2050) and -44.8% (for the OS-5 scenario – combination of Air-to-Water Heat Pump and Air Handling Unit - evaluated in 2080);
- even considering future climate projections, the best HVAC solution was found to be OS-3 (combination of condensing gas boiler and Air Handling Unit), with energy consumption equal to 6.6 $kWhm^{-2}yr^{-1}$ in 2050 and 5.3 $kWhm^{-2}yr^{-1}$ in 2080;
- some energy management strategies may thus imply a more “prompt” response to climate change, but at the same time may tend to “saturate” their beneficial effects in the long term.

Therefore, this work shows the importance of evaluating possible HVAC system solutions taking into account the actual weather conditions that characterize the location of the building, and also their impact during the building lifespan, which will certainly be affected by climate change. Future developments of the work will focus on: (1) the warm season, in terms of cooling energy requirements of the building; Ciancio et al. (2019b) found that the cooling energy need is expected to overpass the heating energy need at least in Southern Europe; (2) the use of renewable energy (especially photovoltaic) for the thermal energy production; (3) application of updated emissions scenarios in accordance with the most recent IPCC assessments.

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CONFLICT OF INTEREST

none

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