Yearly operational performance of a nZEB in the Mediterranean climate

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Over the last decades, the reduction of the energy use in the building sector has become a topic of major investigation and policy development worldwide. Guidelines have been defined to drive governments and building construction stakeholders towards the retrofit of the existing building stock and to the construction of new high-performance buildings. However, availability of operational data is often limited, especially when it comes to high performance buildings in warm climates, although it is essential to define design approaches targeted to energy efficiency, to design smart energy grids and demand-response oriented energy programs. Buildings, such as living laboratories, may offer opportunities to implement and develop energy databases, to provide benchmarks and to study occupant behaviour under different operational conditions.

The paper investigates the energy and thermal comfort performance of a residential building in the Mediterranean climate. The building, certified as Passivhaus and equipped with an advanced monitoring system, allows to test different control strategies, to study occupant behaviour and to provide real time operational data. In particular, the data analysis showed a positive energy balance on yearly basis, i.e. an energy use of 59.7 kWh/m^2_{net}/year vs. an on-site energy generation of 76.0 kWh/m^2_{net}/year. The energy breakdown highlighted, that energy uses related to user behaviour and comfort requests account for about 72 % of the total energy use, confirming that occupant behaviour is one of the major drivers of the operational energy use (and the related services) in high performance buildings.

Keywords: high performance building; Passivhaus; Passive house; nZEB; living lab; Mediterranean climate; energy breakdown; energy monitoring; comfort monitoring.

1. Introduction

Buildings are responsible for approximately 40 % of energy consumption and 36 % of CO_2 emissions in the European Union [1,2]. Improving energy efficiency and reducing pollutants emissions are, therefore, primary objectives of European directives (e.g. European Directive 2010/31/EU [3]), guidelines and protocols. In terms of energy efficiency in buildings, the European Directive 2010/31/UE [3] has required the Member States to update the minimum energy performance requirements for both new buildings and existing ones that undergo energy renovation, also introducing the concept of nearly zero energy buildings (nZEB) as a key element of EU energy policy.

In northern European countries, and in particular in Germany, the experience gained since the early 1990s had led to the development of standards and guidelines for the design and construction of passive houses and of high energy performance buildings. In 1988 the first formally defined passive protocol was established under the name of “Passivhaus” and in 1991 it was applied to a small condominium in Darmstadt (Germany) with the aim of creating a pilot energy-efficient building suitable for the northern climate [4]. The Passivhaus standard was, indeed, originally developed for countries with a cold climate (e.g. Germany and Sweden), where the major challenge is to contrast the low outdoor temperature and to wisely exploit the internal and solar heat gains, while providing adequate indoor air quality levels. Cooling and dehumidification are usually less important in cold climates, especially for residential buildings [5]. The standard Passivhaus was subsequently extended, under the Passive-On project, to warmer climates in order to explicitly include energy needs for cooling [6–8]. Therefore, the current requirements to comply with the Passivhaus certification include (for the “Classic” criteria[1]): energy need for space heating lower than 15 kWh/m^2/year, rate of air infiltration at 50 Pa (n_{50}) lower than 0.6 air change rate per hour (ACH), and energy need for cooling lower than 15 kWh/m^2/year, with an additional allowance for dehumidification [9,10]. Under the new criteria introduced in 2015 it is assumed that 100 % of grid energy would come from renewable sources, and renewable primary energy factors are calculated taking into account the losses due to inter-seasonal storage and considering the amount of inter-seasonal shift necessary for each climate. Renewable primary energy use (PER use) for all domestic energy services (heating, cooling, hot water and electricity for lighting and

[1] According to Passivhaus standard, buildings may be classified as Classic, Plus or Premium.

appliances) must be lower than 60 kWh/m^2/year for the "Classic" criteria[2], referring to the net conditioned floor area of the building. According to Directive 2010/31/UE, the nearly zero or very low amount of energy required by a nZEB, should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby. Depending on the national definition of the term "nearby", a certified Passivhaus building is de facto a nZEB, since 100 % of the energy use is assumed to come from renewable, or it can easily become a nZEB, if the reduced energy needs are balanced by a significant exploitation of renewable energy sources on-site. An on-site renewable energy generation criterion, is, indeed, already included by the Passivhaus standard for the "Plus" and "Premium" qualification; it must be respectively higher than 60 kWh/m^2/year and 120 kWh/m^2/year, where the square meters are those of the footprint area of the building.

If compared to the cold climate of Northern Europe, the Mediterranean climate of Southern Europe (Csa/Csb - under the Köppen climate classification [11]) is characterized by relatively mild winters and very warm summers. The abundance of solar radiation can guarantee an easy exploitation of solar energy for the production of electrical energy through photovoltaic (PV) systems and/or thermal energy through thermal solar systems. At the same time, the high solar irradiance exposes the buildings to significant solar heat gains that must be carefully controlled by solar shading devices and ventilation systems to prevent overheating and thermal discomfort; this will avoid, or significantly reduce, the use of air conditioning systems. In passive buildings, an accurate control of solar gains is always required, because sufficiently ample charge/discharge loops of building thermal mass may not be provided by means of night-time ventilative cooling, under extreme heat gains conditions [12–14]. In the Mediterranean climate, thus, the two concepts of passive house and nZEB, find a very challenging environment, which requires an explicit definition of the comfort objectives and particular care both during the design and the operational phase [15].

However, literature on operational data of high performance residential buildings in Mediterranean climate is still limited, and benchmarks are missing. Wassouf [16] reports comfort monitoring data of two detached Passivhauses in Spain, whereas Erhorn and Erhorn-Klutting [17,18] selected examples of nZEBs providing calculated and/or monitored energy performance of residential and non-residential buildings in twenty European countries including Italy, Malta and Portugal. In particular, monitored energy use for heating (25.81 kWh/m^2/year), for domestic hot water (DHW) (2.05 kWh/m^2/year) and for lighting (14.88 kWh/m^2/year) are reported for a residential building located in Trino, in the North of Italy (Vercelli, Cfa - under the Köppen climate classification), besides a PV production of 17.32 kWh/m^2/year and a total primary energy use of 23 kWh/m^2/year. The Portuguese building described by Erhorn and Erhorn-Klutting [17], is not residential, and data provided for Malta are calculated with an energy performance certification software. Mihai et al. present energy use for heating (13.12 kWh/m^2/year) and PV production (11.12 kWh/m^2/year) for a passive house located in Bucharest (Cfa - under the Köppen climate classification) [19]. Mutani et al. [20] report energy need for heating and global energy use data for ten residential nZEBs built in Piedmont (North of Italy), all equipped with air-to-air or air-to-water heat pumps. According to the authors, the energy need for heating of the ten nZEBs varies between 10.72 kWh/m^2/year and 16.97 kWh/m^2/year, whereas the energy use for space heating, cooling, DHW and electric appliances varies altogether between 9 kWh/m^2/year and 15 kWh/m^2/year (it is lower than the energy need due to the effect of the heat pump). Finally, Ascione et al. [21] report early results of a monitoring campaign carried out to assess energy and environmental performance of a residential nZEB, in the South of Italy, located in Benevento (Csa - under the Köppen climate classification). However, monitoring data reported by Ascione [21] do refer only to ten days of summer 2018 (from 20th to 30th July 2018).

Other available data refer mostly to high performance and Passivhaus certified buildings located in continental climates; e.g. Tanasa et al. [22,23], present energy and thermal comfort monitoring data of a passive house in Timisoara, Romania (Dfb - under the Köppen climate classification), whereas Zavrl and Stegnar [24] report a comparison of simulated and measured energy performance for a nZEB in Ljubljana, Slovenia (Dfb - under the Köppen climate classification).

[2] The requirements for the PER demand and generation of renewable energy were first introduced in 2015. As an alternative to these two criteria, evidence for the Passive House Classic Standard can continue to be provided in a transitional phase by proving compliance with the previous requirement that total primary energy demand (PE) of QP ≤ 120 kWh/(m²/year).

In this scenario, some European projects started dealing with the setup of a common database to provide data of nZEBs in several countries and climates [25]. The ZEBRA2020 project has been developed to monitor the market uptake of nZEBs in target countries and across Europe, and to provide data and recommendations on how to reach a high level of building performance [26]. Pascual et al. [27], in the contest of the ZEBRA2020 project, and Cellura et al. [28,29], report monitoring energy data for the "Leaf House", a nZEB located in Rosora (Ancona, Csa/Cfa - under the Köppen climate classification), Italy. The reported building's energy production by PV is 53.77 kWh/m^2/year, whereas the total energy use is 91 kWh/m^2/year and the use of electricity for heating is 27 kWh/m^2/year.

Through the CEPHEUS project [30,31], 221 passive residential buildings have been analysed according to the Passivhaus standard in five European countries (France, Germany, Austria, Switzerland, Sweden) and measured delivered energy for heating and DHW during the winter period are reported. The results show values of delivered energy for heating between 11.9 kWh/m^2/year and 32.8 kWh/m^2/year, based on the characteristics of the buildings and on the geographical area where they are located, whereas the delivered energy for DHW is between 9.4 kWh/m^2/year and 32.2 kWh/m^2/year, and the electrical energy use between 14 kWh/m^2/year and 49.9 kWh/m^2/year.

Other data reported in the literature for high performance residential building in warm climate, are mainly results from energy simulations and calculations. Simões et al. [32] and Figueiredo et al. [33] report simulation results according to the monthly approach (Passive House Planning Package – PHPP) proposed by the Passivhaus Institute [34] of a real certified passive house located in the central region of Portugal. The monthly approach shows that the energy needs for cooling are completely suppressed, while the energy needs for heating are 7 kWh/m^2/year and the primary energy use is 67 kWh/m^2/year. De Rubeis et al. [35] present energy performance of an energy self-sufficient residential building, located in the outskirt of L'Aquila city, in central Italy. The analysis is performed via energy simulation with EnergyPlus™ and reports energy needs for heating equal to 29.9 kWh/m^2/year. Tsalikis and Martinopulous [36] investigating the PV energy and the solar thermal energy potential production, report simulated monthly cooling (between 1 kWh/m^2/month and 13 kWh/m^2/month), heating (between 0.5 kWh/m^2/month and 21.5 kWh/m^2/month) and DHW (between 1.1 kWh/m^2/month and 2.4 kWh/m^2/month) energy need for typical residential buildings in different Greek cities, whereas Gillén-Lambea et al. [37] report simulated energy needs (between 50 kWh/m^2/year and 60 kWh/m^2/year) of residential nZEBs located in South of Europe to assess the effectiveness of the heat recovery ventilator (HRV) in the achievement of the energy demand goals set by Passivhaus.

Furthermore, within the Passive-On project [7,8] some low-energy residential buildings in Spain, Portugal and Italy were analysed by means of energy modelling software. Building models have been developed and their behaviour has been simulated for a whole year obtaining results of energy needs for heating and cooling in two buildings in Spain, one in Portugal and three in Italy. In the case of Spain and Portugal, the energy needs calculated via simulations are compared with those of standard residential buildings. Table 1 shows the results obtained for a building in Seville and another in Granada; Table 2 shows the results obtained for Portugal and Table 3 shows the results obtained for Italy in three cities: Milan, Rome and Palermo.

Table 1. Calculated energy needs for heating and for cooling related to standard houses and Passivhauses in Seville and Granada.

	Energy needs for heating [kWh/m^2/year]	Energy needs for cooling [kWh/m^2/year]
Passivhaus Seville	2.8	21.7
Standard house Seville	25.8	31.5
Passivhaus Granada	8.7	7.9
Standard house Granada	52.2	16.7

Table 2. Calculated energy needs for heating and for cooling related to a standard house and Passivhaus in Portugal.

	Energy needs for heating [kWh/m^2/year]	Energy needs for cooling [kWh/m^2/year]
Passivhaus	5.9	3.7
Standard house	73.5	32

Table 3. Calculated energy needs for heating and for cooling related to three Passivhauses in Italy.

	Energy needs for heating [kWh/m²/year]	Energy needs for cooling [kWh/m²/year]
Passivhaus Milan	10.4	3.2
Passivhaus Rome	6.2	6.6
Passivhaus Palermo	2.4	9.6

The simulations carried out for the Passive-On project show that the Passivhaus designed in Italy, Portugal and in Granada for Spain, all are able to fulfil the limits imposed to obtain a Passivhaus certification; in Seville, on the contrary, the building exceeds the limit for cooling. However, as mentioned, these are not operational data but data from energy simulations, and as such they include several uncertainties due mainly to: energy simulation approach (e.g. dynamic, quasi-static), reference weather files, occupant behaviour modelling, systems scheduling, material characteristics and installation. Monitoring and verification of buildings' operational performance are fundamental in order to study and assess building's behaviour along the whole buildings' lifetime and under different operational conditions. Moreover, analysis on real data may provide benchmarks for the existing and future building stock, allowing to better design energy grids and flexibility services such as demand-side response programs. Real scale buildings, designed and equipped to perform such as living laboratories, may allow the monitoring and testing of various technologies and their integration in the building's energy concept; they furthermore allow to assess the effectiveness in reducing energy uses and/or increasing indoor environmental quality of the building as a whole [6]. Living labs might also be used to study occupant behaviour, and to check the influence of different operation strategies on the final performance of the building.

This paper reports the results of an energy and environmental monitoring campaign regarding a certified Passivhaus located in Sicily, which provides an exemplary case study for the development of benchmarks for passive houses and nZEBs in the Mediterranean climate. The building was subject to detailed optimization in the design phase [38] and was conceived as a living lab, and therefore equipped with an accurate monitoring system allowing to measure and assess energy and environmental performance both under active space conditioning and free-floating operational conditions. The building is moreover provided with a Building Automation and Control System (BACS) that allows for an accurate control of solar gains and for the study of the effects of different control logics, including the manual control by occupants.

The analysis reports brilliant results both in terms of energy and of thermal comfort performance, paving the way to further studies about the detailed characterisation of installed and prospective technologies, such as the earth to air heat exchanger (EAHE), potential energy storage systems and the effect of automated and manual control logic on buildings' performance.

2. Case study - Building description

The subject of the study is a single family detached house located in the municipality of Mascalucia (Catania, Csa - under the Köppen climate classification), in Sicily. The building has achieved the Passivhaus certification, and it follows the requirements of the certification in term of energy need for space heating lower than 15 kWh/m²/year, energy need for cooling lower than 15 kWh/m²/year, air infiltration at 50 Pa lower than 0.6 ACH, and total primary energy demand for all domestic electric services lower than[3] 120 kWh/m²/year (the current requirements for the PER demand and generation of renewable energy were first introduced in 2015, so they do not apply to the building that received the Passivhaus certification ahead of it). According to simulation results [14,38,39], the house represents an example of nZEB in Mediterranean climate and it was conceived as a living lab, offering the opportunity to test different control strategies and to study the response of the occupants to them. The building does not, however, have a nZEB official certification, since it was built ahead of the enforcement of the law implementing in Italy the nZEB concept.

[3] Value referring to the PHPP certification procedure in place at the time of the building construction permit (2009), which assumed all the electric energy use as being delivered from the grid, and hence weighted with the PEF of the grid.

In order to further check the performance of the house, calculations according the most recent Italian implementation of the nZEB definition have been executed. This latter check has delivered positive results: the building is a nZEB also according to the present legislation and calculation method (Table 4).

Table 4. Requirements for nZEB buildings according to Italian legislation (DM 26/06/2015 [40] *and DLgs 03/03/2011* [41]*), where the values of the various indicators are compared with the respective values of the reference building. (Source: AZEB project, deliverable 2.1)*

DM 26 June 2015 [40]			
Indicator	**Numerical check**	**Unit**	**Description**
$H'_T < H'_{T,max}$	0.19 < 0.55	[W/m²K]	Transmission heat transfer coefficient per unit of *thermal envelope area*
$A_{sol,est}/A_{sup,utile} < (A_{sol,est}/A_{sup,utile})_{max}$	0.0029 < 0.0030	[-]	Equivalent summer solar area per unit of *useful floor area*
$EP_{H,nd} < EP_{H,nd,limit}$ $EP_{C,nd} < EP_{C,nd,limit}$ $EP_{gl,tot} < EP_{gl,tot,limit}$	7.21 < 30.54 10.25 < 18.55 26.21 < 74.75	[kWh/m²/year]	*Energy need for heating* *Energy need for cooling* *Total global primary energy** (includes non-renewable energy and renewable energy)
$\eta_H > \eta_{H,limit}$ $\eta_W > \eta_{w,limit}$ $\eta_C > \eta_{C,limit}$	0.72 > 0.58 0.90 > 0.75 2.09 > 1.17	[-]	Average seasonal efficiency of the winter air conditioning system Average seasonal efficiency of the DHW system Average seasonal efficiency of the summer air conditioning system (includes moisture control)
*includes the following *services/end-uses*: winter air conditioning, DHW, ventilation, summer air conditioning, artificial lighting, transportation of people and things.			

Legislative Decree 3 March 2011 [41]	
Request	**Numerical check**
cover 50% of *primary energy* for DHW through energy produced by RES (*on-site*)	share of renewable: 86.2 %
cover 50% of *primary energy* for DHW, summer and winter air conditioning through energy produced by RES (*on–site*)	share of renewable: 93.1 %
Power of the electrical renewable energy systems installed P ≥ (1 / K) * S [kW]	10.22 ≥ 2.88

The building is an all-electric single-storey house (Fig. 1, Fig. 2), including a basement in which technical and parking spaces are located. The conditioned floor area of the house is equal to 144 m². The building can be operated under a completely passive mode (where comfort objectives are pursued by managing solar gains, ventilation via windows and an EAHE, thermal inertia of the building and of the surrounding soil via the EAHE, etc.) or making use of the active cooling/heating systems.

Fig. 1. External (left) and aerial (right) view of the building.

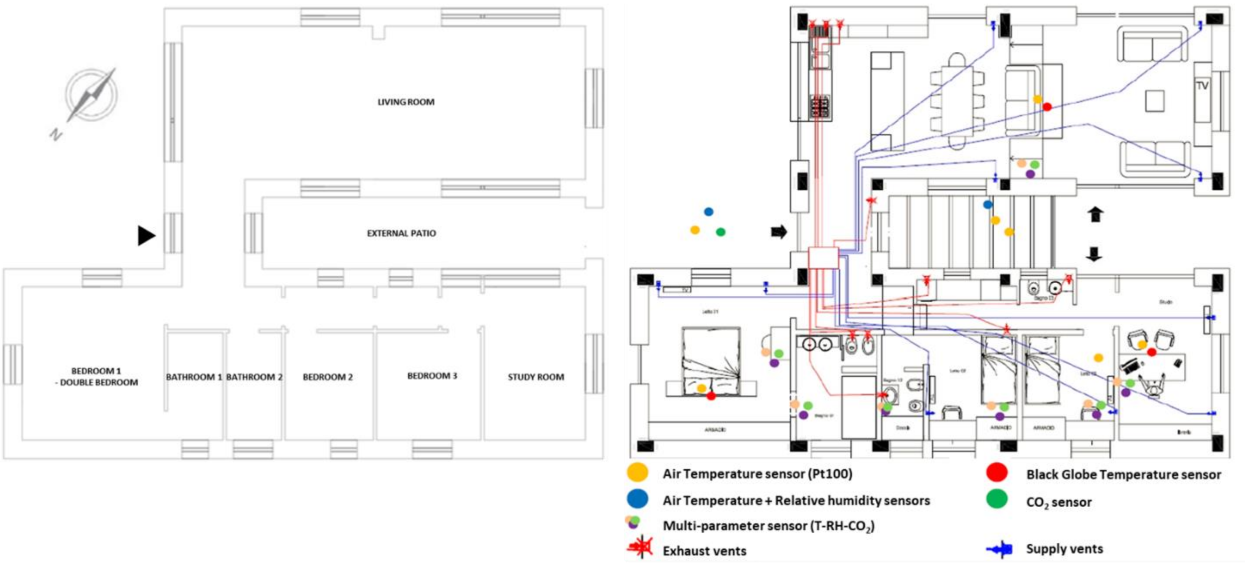


Fig. 2. Plan view of the building and environmental sensors installed.

The high performance of the opaque envelope (Table 5, Table 6) and of the transparent one (windows thermal transmittance: 0.90 – 1.10 W/m^{2}K) is complemented by the local production of renewable energy by means of PV modules, a solar thermal system and by an EAHE, that ensures the pre-heating or pre-cooling of ventilation air, by exploiting the thermal inertia of the soil. The PV system (8.14 kW peak electric power) is installed on the roof and the electricity production by the PV panels is continuously monitored and compared with the instantaneous energy use of the building and the delivered energy (from the grid). An electrical and reversible air to water heat pump (nominal power: 5.49 kW; COP: 3.43) serves the heating/cooling coil in the main inlet ventilation duct and a thermal storage tank (500 litres of hot water), which is also fed by the thermal solar panels integrated in the roof (7 m^2 of flat collectors). During the heating phase the heat pump can deliver energy to the technical storage tank or directly to the coil in the ventilation system, whereas in cooling mode it only produces chilled water to supply the coil. The EAHE provides the possibility for pre-heating or pre-cooling the ventilation air, which may then pass through a heat recovery unit before being treated by the heating/cooling coil and distributed to the rooms (Fig. 3). The exhaust air is extracted from the bathrooms and the kitchen in order to remove the internal pollutants. The EAHE has been designed considering the geometric limits of the lot and the soil type [6,42] and it can be excluded from the ventilation system by means of a by-pass duct, if required, according to the chosen control strategy and the combination of weather-soil-building conditions. Hygrothermal conditions of the air inside the EAHE, the ventilation ducts, the conditioned spaces and of the outdoor environment are monitored by means of sensors as showed in Fig. 2 and in Fig. 3. The system is balanced and does not include additional motorized dampers for regulating the air flow in the rooms. For major details on the EAHE, refer to Carlucci et al. [6,42]. The outdoor window surfaces are protected by motorized solar shading systems, which can be controlled manually or through an automatic system. In order to guarantee an adequate monitoring of the internal microclimate (thermal comfort and air quality), each room is also equipped with temperature, relative humidity and CO_2 concentration sensors (the latter chosen as an indirect indicator of the overall indoor air quality), as can be seen in Fig. 2 (right).

Table 5. Main building envelope solutions.

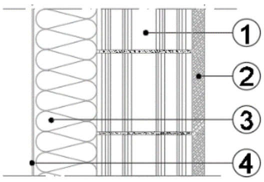
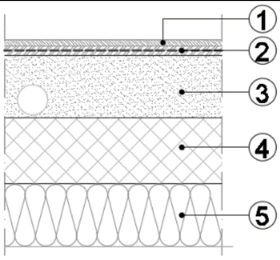
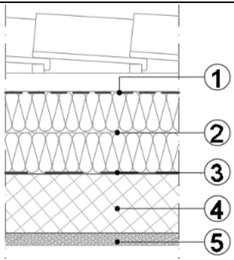
External wall	Basement floor	Roof
		
1. Hollow brick (30 cm) 2. Internal plaster (3 cm) 3. Rockwool insulation (20 cm) 4. External plaster (1 cm)	1. Parquet (2cm) 2. Acoustic insulation (0.5 cm) 3. Expanded clay (20 cm) 4. Reinforced concrete slab (21 cm) 5. Rockwool insulation (10 cm)	1. Impermeable breathable membrane (0.5 cm) 2. Rockwool insulation (28 cm) 3. Vapour barrier (-) 4. Reinforced concrete slab (20 cm) 5. Internal plaster (3 cm)

Table 6. Static and dynamic thermal characteristics of the envelope solutions.

	U [W/m²K]	Y_{12} [W/m²K]	f [-]	Y_{11} [W/m²K]	Y_{22} [W/m²K]	f_R [-]	Time shift [h]
External wall	0.127	0.001	0.012	3.308	1.545	0.898	-0.287
Basement floor	0.231	0.000	0.010	2.117	0.562	0.948	-17.376
Roof	0.130	0.002	0.012	4.861	0.739	0.810	-19.677

note: U is the steady-state thermal transmittance; Y_{12} is the periodic thermal transmittance; f is the decremental factor; Y_{11} is the internal surface admittance; Y_{22} is the external surface admittance; f_R is the internal surface factor.

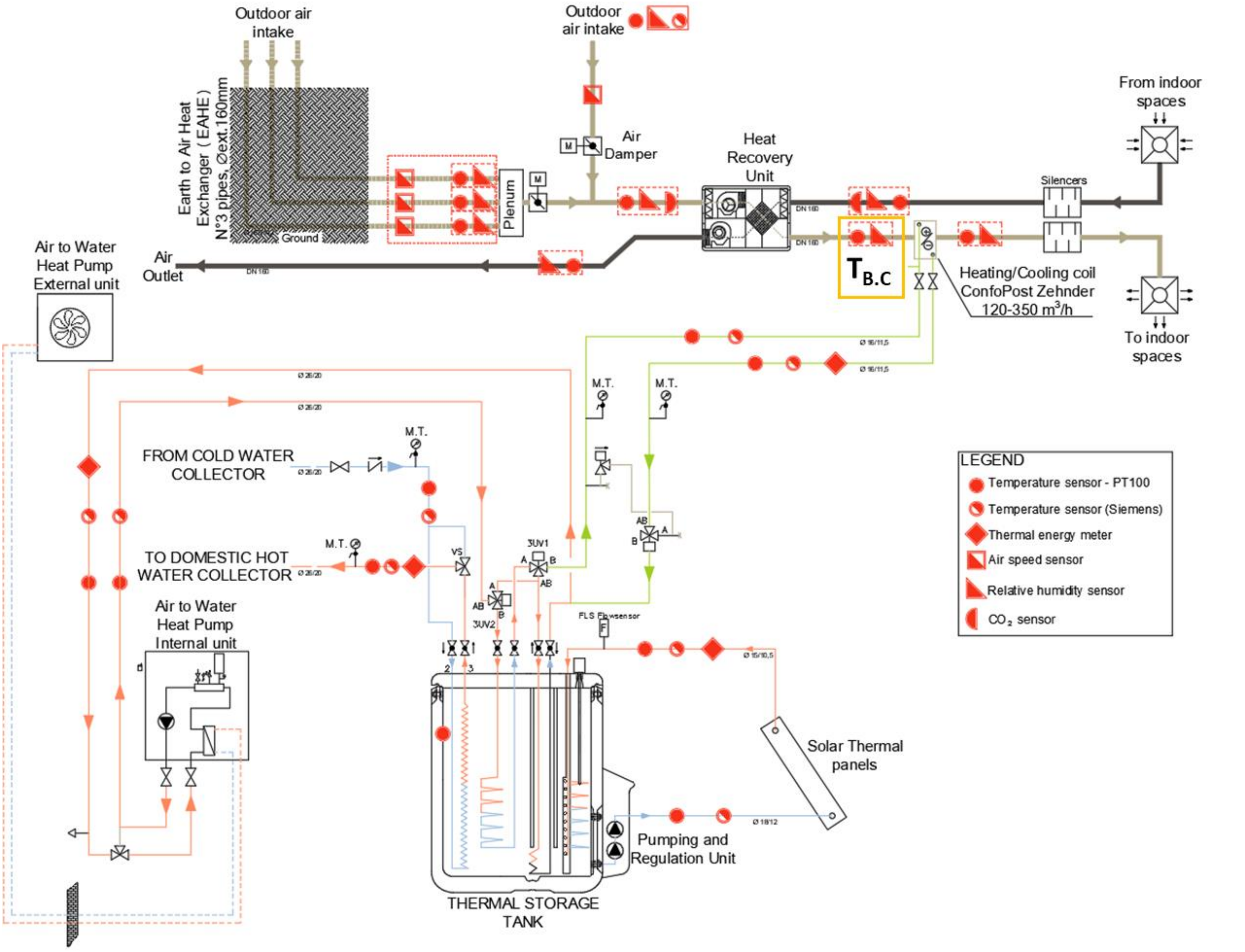


Fig. 3. Graphical scheme of the technical building systems (heating, cooling, ventilation).

A dedicated automatic system has been designed and installed to provide an adequate control of the building and of its services systems. It allows also for the detailed monitoring of energy and comfort performance. The control and monitoring system consists of two main parts, developed and integrated at different times. The first one is devoted to the monitoring of indoor environmental parameters and to the basic control of shading devices and of the heat pump. It is based on the Konnex (KNX) standard and communication protocol [43]. The second part integrates and supervises the first and it is based on the BACnet communication protocol [44]. It includes the data acquisition from sensors positioned in a large number of monitoring points in the conditioned areas, the EAHE, the soil, the courtyard, the relevant elements of the building active and passive systems, domestic electric appliances and lighting, and it allows for the implementation of further control algorithms for the heat pump and the ventilation systems. Finally, the thermal energy meters, installed along all the hydraulic loops, are communicating by means of the Meter-Bus (M-Bus) protocol [45,46] also integrated and supervised by the BACnet system. The structure of the entire system is reported in Fig. 4.

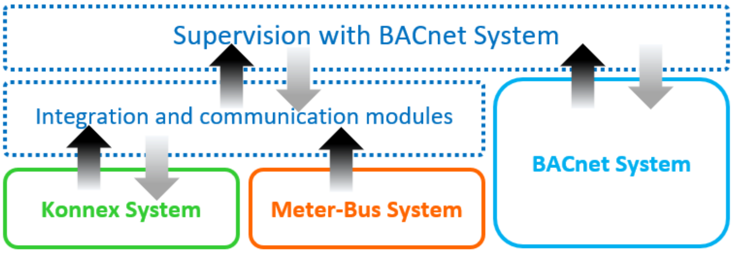


Fig. 4. Scheme of communication and supervision protocols.

All the control strategies and the parameters can be monitored through the integrated management platform *Desigo™*. The parameters are recorded at a fixed frequency of 5 minutes, except for the opening of the windows and the position of the solar shadings, which are recorded at each change of status.

3. Boundary conditions

The analysis of the building performance in summer (cooling), winter (heating) and in intermediate conditions has been carried out in relation to three boundary conditions (i.e. weather conditions, presence of occupants and control strategies implemented) between the 1st July, 2017 (01/07/17) and the 30th June, 2018 (30/06/18). The three boundary conditions are briefly described in the following sessions.

3.1 Weather condition

Fig. 5 reports the evolution of the weather conditions as monitored by a weather station installed on the roof of the building. The red dotted vertical lines indicate the sub-division between the months, from July 2017 to June 2018. The daily temperature variation range (daily maximum and daily minimum of the five-minute interval) is considerably wider in summer than in winter (Fig. 5a), this indicates favourable boundary conditions for night-time ventilative cooling during summer months. The maximum temperature value (39.3 °C) is recorded in July; however, August has been the warmest month among those monitored, maintaining very high and more constant temperature values, even during the night, especially in the first ten days of the month. After the first half of August, the temperatures, with some fluctuations, have decreased to reach the coldest temperatures (0.5 ° C) in the months of December 2017 and February 2018.

The outdoor relative humidity is analysed with the same approach (daily maximum and daily minimum of the five-minute interval) (Fig. 5b). It shows the opposite trend of the temperature; low relative humidity values correspond to high temperature values, and vice versa. Moreover, the trend of the external relative humidity is influenced by the precipitation events recorded during the entire monitoring period. During the months of July and August 2017, when very high temperatures are recorded, the relative humidity is within the range 13 - 60 %. Whereas, between September and October, the relative humidity reached higher values due to the frequent precipitations. Finally, in correspondence with the highest temperatures recorded at the end of April and at the beginning of May, the relative humidity registered very low values, close to 20-30 %.

Fig. 5c shows the maximum global hourly solar irradiance values recorded in the whole monitoring period. On average, it shows a daily bell-shaped distribution and maximum solar irradiance values around 950-1000 W/m^2, recorded in the summer months. The wind speed and the wind direction are summarised by means of a wind rose as reported in Fig. 5d. The wind rose displays the cardinal directions: North, East, South, and West, and their intermediate points. The figure summarises the quantity of values recorded, with a five-minute interval, for a certain direction and a certain wind speed, during the investigated period. In summary, the wind blows mostly from South-West (16 %), from South (12 %) and from North (9 %) with different wind velocity, but, for most of the time, lower than 5 m/s.

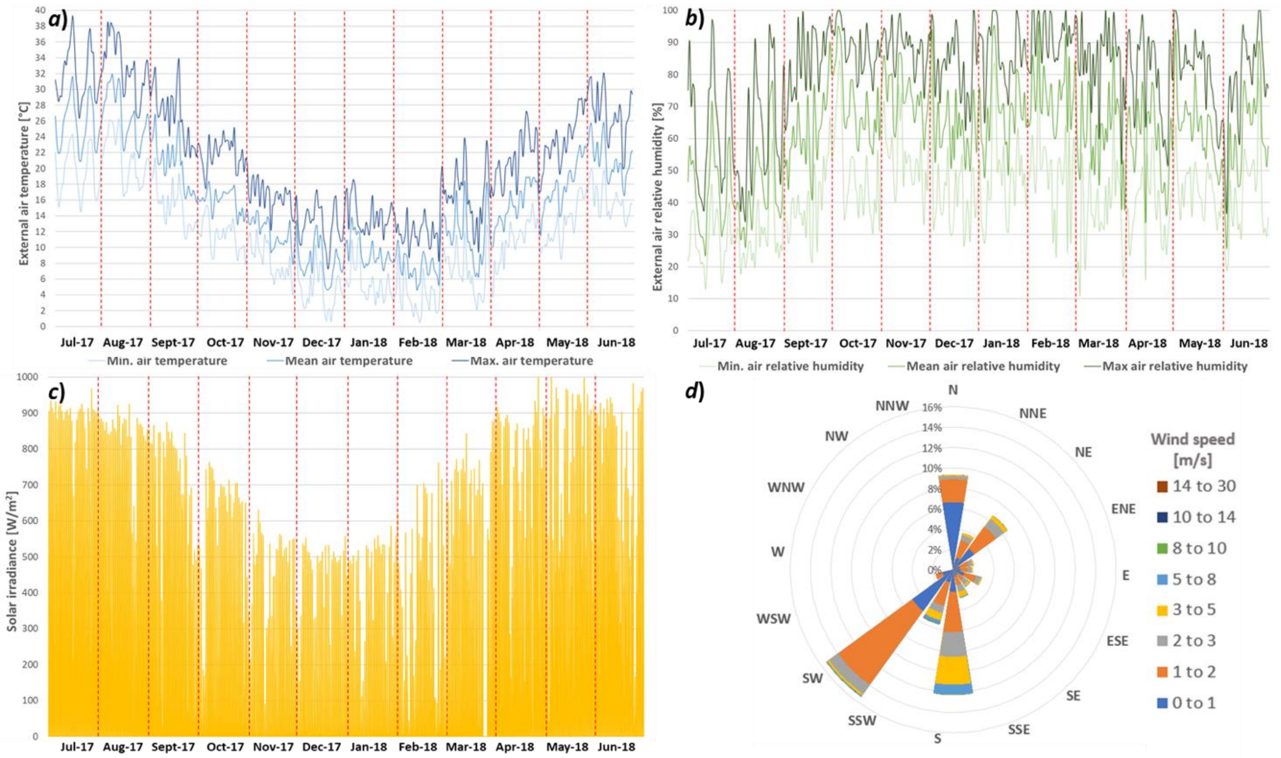


Fig. 5. Measured weather data in the monitoring period (01/07/2017 – 30/06/2018): a) Daily min, mean, max outdoor air temperature; b) Daily min, mean, max outdoor relative humidity; c) Maximum global hourly solar irradiance; d) Wind rose.

3.2 Occupation condition

The building is conceived as living lab, thus occupied by real users whose presence has influenced the operation of technical building systems and the activation of the control strategies [47], but it has indirectly provided information on users' perception of the environment. During the period of the analysis the house has been occupied by one, two or three persons; erratic occupation has been recorded during July 2017 and June 2018, whereas during the other months the building has been occupied more regularly. Occupation conditions have been obtained through users' interviews and the monitoring of energy use of reference domestic appliances such as the induction hob, the oven and the washing machine. The building was not occupied during some days of September (7th-11th September).

During the monitored period, different control strategies have been implemented to regulate the use of natural and mechanical ventilation, solar shadings and active cooling with heat pump, giving priority to the use of passive and low-energy solutions. In addition to the electrical services for lighting and appliances, users of the building are also able to modify some settings of the control logics by means of the *Desigo™* interface. They can manually control the settings of the heat pump (deactivation of the heat pump), the mechanical ventilation (by opening windows, that are provided of sensors that stop the fans) and of the solar shadings (by lowering or raising the shadings and by setting the orientation of the louvres).

3.3 Control strategies

3.3.1 Natural ventilation

The natural ventilation (NV) strategy is activated through the manual opening of windows and is detected and registered by the KNX bus by means of an electrical contact installed on each window. The status of the windows is detected and memorized by the system which activates or deactivates the mechanical ventilation (MV) accordingly. However, the control system can also send messages to the building occupants (via SMS, e-mail, or a PC interface) to suggest the most suitable operation of windows according to the indoor and outdoor temperature. Natural ventilation has been chosen by the occupants, almost continuously, in three periods of time: during the second half of July 2017 to the end of the month, from the second half of August to the end of September 2017 and from the second half of May 2018 to the end of June 2018. Moreover, to passively cool the building structure and to evacuate solar and internal gains, the natural ventilation (cross ventilation) was exploited during the night-time [12,48] on the first half of August. The black line, referred to the right axis, in Fig. 6 represents the instantaneous electric power recorded at each time step (five minutes) for the mechanical ventilation system. Natural ventilation is exploited when the black line indicates 0 kW. In the same figure the blue line, referred to the left axis, represents the instantaneous electric power required by heat pump.

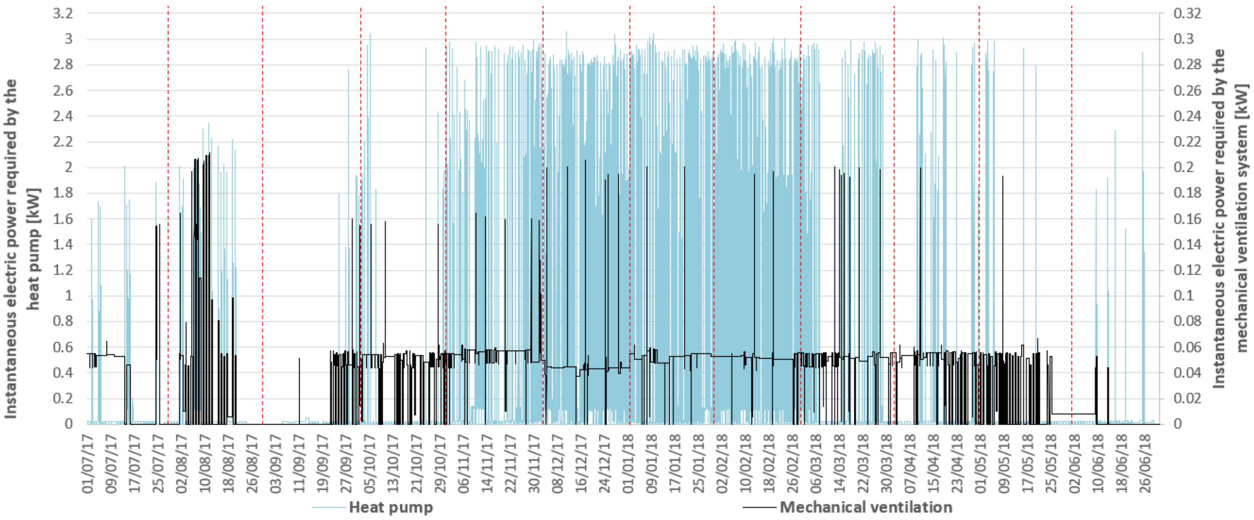


Fig. 6. Instantaneous electric power required by the mechanical ventilation system (black line - referred to the right axis) and instantaneous electric power required by the heat pump (blue line - referred to the left axis) during the investigated period.

3.3.2 Mechanical ventilation

Mechanical ventilation is activated if all the windows and the entrance door are closed. The ventilation system is balanced and a demand controlled mechanical ventilation (DCMV) has been chosen as a ventilation strategy. This strategy allows to adjust the speed of ventilation fans according to some measured environmental parameters [49] via proportional control loops. In this case, the speed of ventilation fans has been chosen as a function of CO_2 concentration (ppm) averaged over all the rooms and the indoor air temperature of the living room. According to the DCMV settings, the speed of ventilation fans is adjusted proportionally to the distance from the respective set-point values of the chosen variables (CO_2 concentration and temperature); the two set-points can be selected by the user. For this campaign the set-point values have been fixed at: 1000 ppm for the CO_2 concentration and 26 °C for the indoor air temperature during the cooling season, and 19 °C for the indoor air temperature during the heating season. In this way, the maximum air velocity value derives from the maximum internal temperature or CO_2 concentration limit values, set to guarantee an adequate level of air quality and comfort. The air speed is governed according to the most unfavourable conditions between the two.

3.3.3 Cooling mode

In summer, the cooling mode control takes into account the indoor and outdoor air temperatures and the air temperature at the exhaust of the EAHE. When all the windows are closed and the indoor air temperature of the living room is higher than the set point value ($T_{ind.SP.C}$ = 26 °C), the control system automatically selects the use of the EAHE or of the outdoor air as supply to the ventilation system if either of them is below 26 °C. In particular, if the air temperature at the exhaust of the EAHE is lower than the outdoor air temperature, the system opens the dampers to supply air from the EAHE, otherwise the system bypasses it, supplying air directly from outdoor. With similar inputs, the activation of the heat pump for delivering chilled water to the cooling coil occurs, as described in Fig. 7:

1. if all the windows and the doors are closed and the indoor temperature of the living room (the set point temperature ($T_{ind.SP.C}$)) exceeds the value of 26 °C;
2. and if the air temperature before passing into the cooling coil ($T_{B.C.}$, see Fig. 3) is higher than a maximum temperature value that can be set as the difference between the indoor set point temperature ($T_{ind.SP.C}$ =26 °C) and a reference value (here ΔT_{FC1} = 6 °C), then the cooling coil is activated. In this case, if the air temperature before passing into the cooling coil ($T_{B.C}$, see Fig. 3) is higher than 20 °C (or $T_{ind.SP.C}$ (26 °C) - ΔT_{FC1} (6 °C)), the cooling coil is activated. Otherwise the speed of ventilation fans is selected based on the control diagram of the indoor air temperature of the living room or of the CO_2 concentration value inside the house.

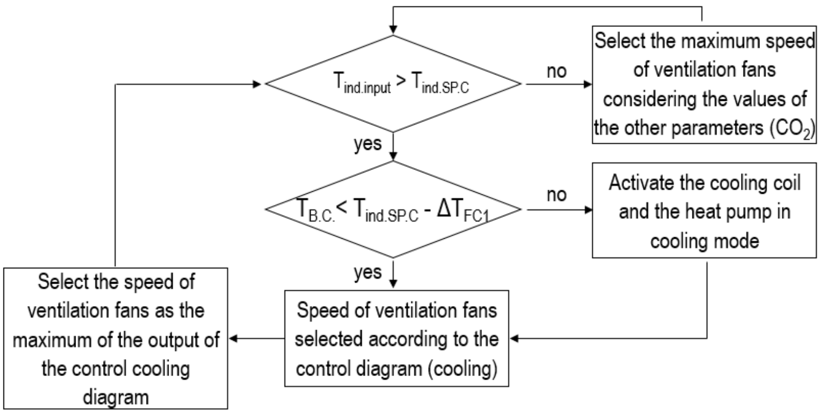


Fig. 7. Cooling mode control scheme; $T_{ind.SP.C}$ = 26 °C; ΔT_{FC1}=6 °C.

The manual control by building's users is always possible and they can modify the set control logics. Indeed, in some days of summer, the activation of the heat pump in cooling mode was governed according to the user's preference and not according to the automatic control logic. In a living lab, the activation of control strategies interacts with users' preferences and choices. On the one hand this can lead to less controlled conditions, on the other, it allows the monitoring of the occupants' behaviour and preferences. This represents a valuable aspect in studies on operational energy and comfort performance.

During August 2017, the building was cooled during the day with mechanical ventilation and, when necessary, with the activation of the heat pump; at night-time, the ventilative cooling passive strategy was chosen [5], with the exploitation of natural ventilation through the windows. From the second half of the month the mechanical ventilation and the active cooling mode have been deactivated in favour of the exploitation of natural ventilation during all the daytime.

3.3.4 Heating mode

In the heating period, according to Italian regulation (D.P.R. n. 412/1993, [50]) from 15th November to 31st March in Mascalucia, the mechanical ventilation and the heat pump followed the control logic described in Fig. 8. When all the windows are closed and the minimum temperature of all monitored rooms in the house ($T_{ind.input}$) is lower than the set-point temperature for heating ($T_{ind.SP.H}$ = 19 °C), the heat pump and the heating coils are activated in heating mode. Furthermore, the control logic verifies the possibility of cooling using an enhanced flow of outdoor air via mechanical ventilation (without the activation of the cooling coils) if the indoor temperature ($T_{ind.input}$) is higher than the cooling set-point value considered for the heating period ($T_{ind.SP.C}$ = 28 °C). This allows to maintain the indoor air temperature between the heating set-point values and a higher threshold to prevent overheating ($T_{ind.SP.C}$ = 28 °C) in milder winter days or when there is abundance of solar radiation or internal heat gains.

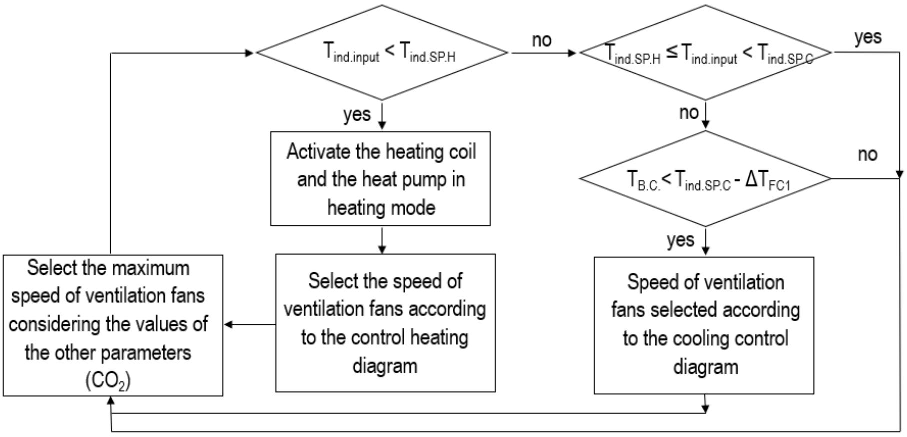


Fig. 8. Heating mode control scheme; $T_{ind.SP.H}$ = 19 °C; $T_{ind.SP.C}$ = 28 °C; ΔT_{FC1} = 10 °C.

4. Results

All the energy uses, including those related to cooking and garden irrigation, are measured by means of the monitoring system. The campaign allowed to study the building's performance both in heating, cooling and free-floating operational conditions, from the energy and environmental point of view. The following sections report the energy and environmental results of the monitoring campaign and includes: the total energy use, the production by the PV, the grid interaction, a detailed breakdown for the main energy services of the building and a detailed thermal comfort analysis.

4.1 Global energy performance

The total electric energy use related to the conditioned spaces and the service spaces (i.e. garage, outdoor lighting, etc.) recorded during the monitoring campaign is 8598.7 kWh/year, corresponding to 59.7 kWh/m^2_{net}/year of conditioned floor area. This is largely overcome (on a yearly basis) by the electrical energy production by the PV system installed on the roof, that is 10946.4 kWh/year or 76.0 kWh/m^2_{net}/year of conditioned floor area. Fig. 9 shows on a monthly and yearly basis, the energy production by the PV system in green, and the total energy use in red. On a monthly basis, the energy balance of the building is slightly negative only during the winter months of November, December, January and February, due to a higher use of the heat pump for heating and production of DHW. The total energy use varies from 2.9 kWh/m^2_{net}/month in July 2017, when the house has been occupied in a discontinuous way, to 7.5 kWh/m^2_{net}/month in December 2017, when very low outdoor air temperatures have been recorded and the building has been regularly occupied. On the other hand, the monthly production of electrical energy by PV (normalised to the net floor area of the building) shows the minimum values of 3.6 kWh/m^2_{net}/month in February 2018 and a maximum value of 9.1 kWh/m^2_{net}/month in July 2017. In terms of primary energy assuming again (for uniformity with the original PH certification procedure) that all the electric energy use is delivered from the grid, and applying the relevant total Primary Energy Factor (PEF) equal to 2.42 for electrical energy from the grid [40] to the monitored yearly total energy use[4], the building shows a total primary energy use of 144.5 kWh/m^2_{net}/year, that can be considered in line with the limit imposed by the Passivhaus standard when the house was designed, built and certified, i.e. 120 kWh/m^2_{net}/year for all domestic application [51]. The above total primary energy use (144.5 kWh/m^2_{net}/year) is, indeed, calculated by considering all the services of the house, including those not related to the boundary of the net conditioned area, such as irrigation pumps,

[4] In this case, the total electric energy use corresponds to the total electric delivered energy.

external lighting system, services for the parking space. Unfortunately, these services are monitored together with the others of the building, via the same meter, and cannot be separated. Moreover, it is worth noting that the value of primary energy depends on monitored operational and occupation conditions, while the limit defined by the certification criteria refers to standard calculation procedures, based on average and standard conditions. The Heating Degree Day (HDD), calculated according to ISO 15927-6:2007 [52] considering the heating season from 15/11 to 31/03, equal to 1455 HDD, are higher than the standard 1271 HHD reported in the Italian regulation (D.P.R. n. 412/1993, [50]) for Mascalucia; this indicates that the climatic conditions recorded in the analysed heating season have been more challenging than the reference conditions for the same location. Finally, it should be noted that a great uncertainty is related to the user's behaviour, which rarely corresponds to the standard calculation conditions. Therefore, considering the uncertainties due to the operational, weather and the occupation conditions, the resulting yearly primary energy measured for the investigated year can be confidently considered in line with the limits imposed by the Passivhaus certification.

Fig. 9. Monthly and yearly energy production by PV (green) and total energy use (red) during the investigated year.

In terms of electric power (Fig. 10), the required instantaneous power measured at each time step (red line) never falls below 400 W. This threshold value, which is almost constant (including night-time), is due to the power required constantly by: the refrigerator, the anti-theft system, the control and monitoring system (PLC, electronic modules, supervision computer, etc.), and the stand-by of the typical household electrical appliances (televisions, coffee machine, etc.). The visible peaks of about 5-6 kW recorded in winter months are due to the use of the heat pump for heating and for the production of DHW. Considering the PV production, peaks of about 5 kW of electric power are reached almost every day, but values up to 7-8 kW have been recorded in cases of particularly clear sky. Fig. 10 shows that, although peaks due to energy use and to PV production both happen during the day time, a slight mismatch between production and use is possible. Moreover, generation typically overcomes the use during the central hours of the day, and in case of low occupancy rate, also during the whole day time. Peak shifting solutions could definitely allow increasing the on-site use of PV generated energy, thus reducing the use of the national supply grid as an off-site storage, as shown in the following section.

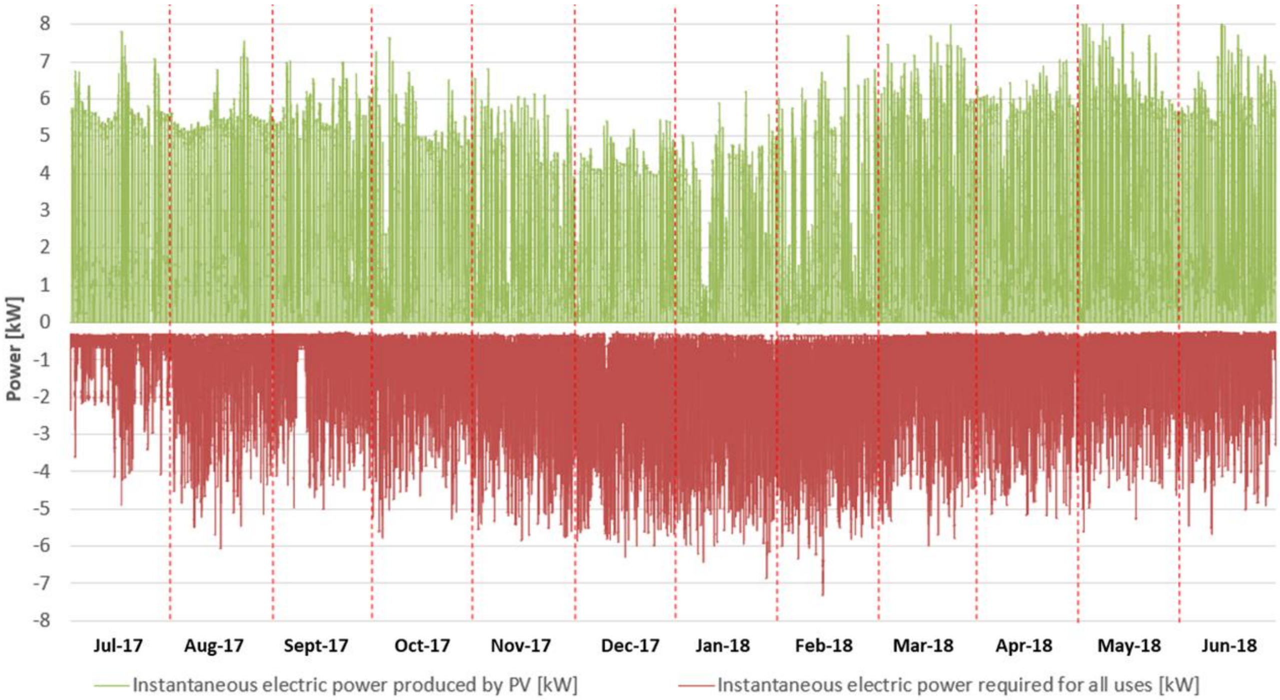


Fig. 10. Instantaneous electric power produced by PV system (green) and required for all services of the building (red).

4.2 Grid interaction

An important aspect to be considered is the interplay of renewable energy generation and the energy load of buildings in terms of grid interaction [53,54]. During the monitoring period, for most of the time the electrical energy produced by the PV system is higher than the total energy use of the building. The building is, therefore, a "prosumer", suppling a considerable amount of energy to the national grid. When dealing with these types of buildings, quantitative indicators can be used to describe load matching and grid interaction conditions. Load matching indicators measure the degree of overlap between production and load profiles (e.g. the percentage of load covered by on-site generation over a period of time), whereas grid interaction indicators take into account unmatched parts of production or load profiles (e.g. peak powers delivered to the electricity distribution grid) [55]. Therefore, an insufficient management of load matching and grid interaction issues in high performance buildings, such as Passivhaus or nZEB, may not lead to the achievement of a full potential in terms of optimization of energy usage and maximization of energy self-consumption.

To analyse the interaction of the building with the grid, typically, the Load Cover Factor (γ_{load}), is used, representing the percentage of the energy use covered by on-site electricity production and defined as follows [54,55]:

$$\gamma_{load} = \frac{\int_{\tau_1}^{\tau_2} \min[g(t) - S(t) - \zeta(t),\ l(t)]dt}{\int_{\tau_1}^{\tau_2} l(t)dt} \qquad [\text{-}] \qquad \text{(Eq. 2)}$$

Where:

$l(t)$ energy load,

$g(t)$ on-site electricity production,

$S(t)$ stored energy,

$\zeta(t)$ energy losses.

In this analysis, the terms related to energy storage and losses are equal to zero. Following the expression of Eq. 2, the indicator is assuming values between 0 and 100 % or 0 and 1. This, nevertheless, does not allow to evaluate the potential of the building in terms of compensation and overcoming of electrical loads, because the indicator is saying when the load is covered, i.e. 1, but not if this is overcome and how much.

The analysis has therefore been carried out considering a new factor that we can call Balance Factor and express as the ratio between energy production by PV and the total energy use, calculated on daily basis as follows:

$$BF = \frac{\int_{\tau_1}^{\tau_2} [g(t) - S(t) - \zeta(t)] dt}{\int_{\tau_1}^{\tau_2} l(t) dt} \qquad [-] \qquad \text{(Eq. 3)}$$

Ideally, this indicator should be equal to 1, in well balanced systems (i.e. when an appropriate storage system is installed and no loss is experienced). Nevertheless, it also admits values that exceed 100 % or 1 (Fig. 11), when the production is higher than the use, and no storage is provided; as for the case under analysis. On daily basis, the calculated Balance Factor shows values between 0 (when the PV production is null) and about 4.5, a value recorded during a particularly sunny day in summer months with very low internal heat gains. In summer months this factor has registered values always higher than 1, while in the central winter months the Balance Factor is almost always lower than 1. Considering the whole monitored year, 63 % of the Balance Factor values are higher than 1, whereas in the heating season this percentage decreases to 20 %. Considering the obtained results, the building, if integrated with an energy storage system, could maximize the electricity self-consumption and bring to zero the amount of energy sold to the grid (i.e. a full on-site use of the PV generated energy), at least during the summer months. In order to understand if this solution may have a reasonable payback time, and a sound technical value, a Life Cycle cost/benefit analysis should be performed, considering different kinds of commercial solutions and battery sizes, for example using the Cost-optimal methodology of the European Union [56], where a reference building is identified (in this case the current building condition) and a set of technical solutions is applied to it, evaluating their effect both in terms of energy performance and cost. The cost-optimal level is defined as "the energy performance level which leads to the lowest cost during the estimated economic lifecycle", and it should take into account a range of costs including investments, maintenance, operating costs and energy savings [57].

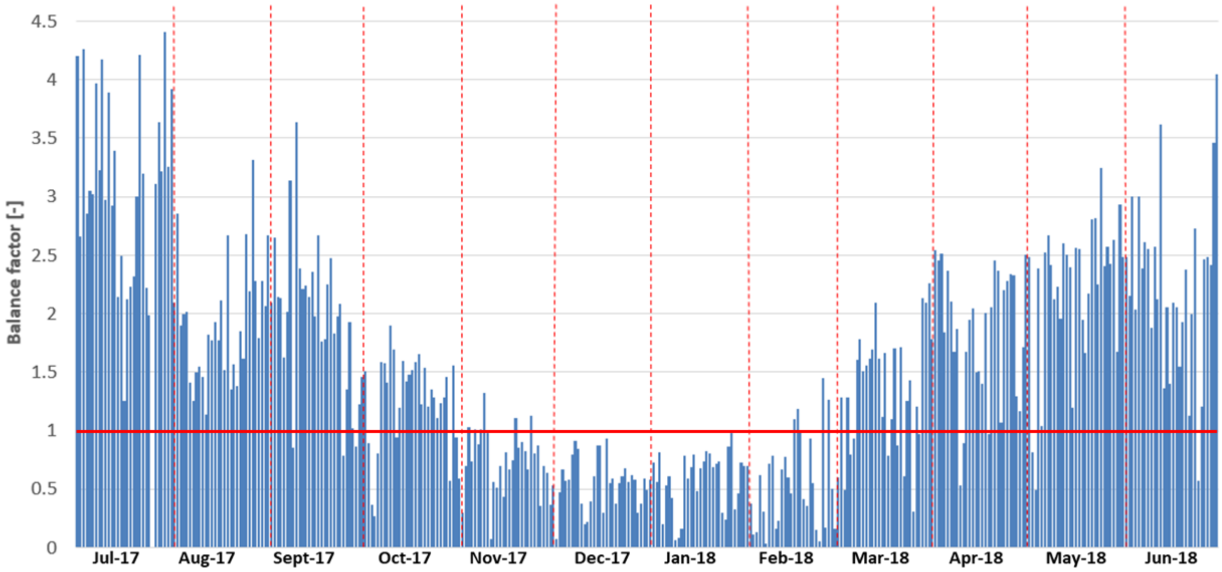


Fig. 11. Balance factor calculated on daily frequency for the whole monitored period.

4.3 Energy breakdown

The building is all-electric and equipped with electricity meters to monitor all the building energy services; this allowed to calculate, for selected periods of time, specific consumption indices and to create a detailed breakdown for end-uses. Results are reported in Fig. 12 for the heating period and for the whole monitored year, where the different colours indicate the various services in the house. During the heating season the energy use for heat pump represents 24 % of the total energy use, followed by the home automation and anti-thefts protection, that also includes the control system of environmental and energy parameters for monitoring purpose, with 12 % of the total energy use. Considering the whole monitored year, the two energy services are comparable and equal to 16 % of the total yearly energy use. The energy use of the home automation is quite constant during the year, while the heat pump energy use is more occupant-dependent and varies according the period of the year. During the heating season, the heat pump serves the heating coil and produces DHW, while during cooling and free-floating operational conditions the heat pump serves the cooling coil, when an active strategy to cool the building is necessary and preferred by the occupants, and produces DHW. Fig. 6 highlights in blue the electric power required by the heat pump during the whole year. It can be noted that the heat pump has been constantly used to provide heat during the heating season and used in a more variable way during the rest of the year, when passive strategies have been preferred. The mechanical ventilation system and the oven share of the total energy use is about 4 %, both in the heating season and during the whole year. The refrigerator represents respectively 3 % and 5 % of the total energy use during the heating season and during the whole year, while the energy use of the garden irrigation pumps is respectively about 0 % in the heating season and 2 % for the whole year. The refrigerator energy use is higher during the summer and the free-floating period since it is influenced by the higher internal air temperature of the building. The garden irrigation pumps energy use is influenced by rainy events, more frequent during the winter season. The remaining services (lighting and other plug loads such as TV, microwave, notebook, etc.) weigh for 48 % and 46 % during the heating season and the whole year respectively. These include indoor and outdoor lighting, individually unmonitored appliances, televisions, electrical equipment temporarily connected to electrical plugs (such as laptops, cell phones, hair dryers, etc.), etc. Vacuum cleaner, induction hob, dishwasher, oven, coffee machine, clothes dryer and washing machine, altogether, account for 10 % of the building energy use along the year. It means that about 56 % of the energy use of the building is depending on occupants' choices and preferences, excluding thermal comfort. When including the latter, the share of the total energy use directly affected by occupant expectations and behaviour rise to 72 %, a quite impressive number. Since these kind of data are not available for other buildings it is not possible to say if they represent a best, average or worst scenario, corresponding to austere, average and wasteful users; nevertheless, they represent an important signal for both designers and policy makers, providing a sound evidence of the huge role played by occupant behaviour on buildings' energy use, especially in the case of high performance buildings, such as nZEBs and passive houses.

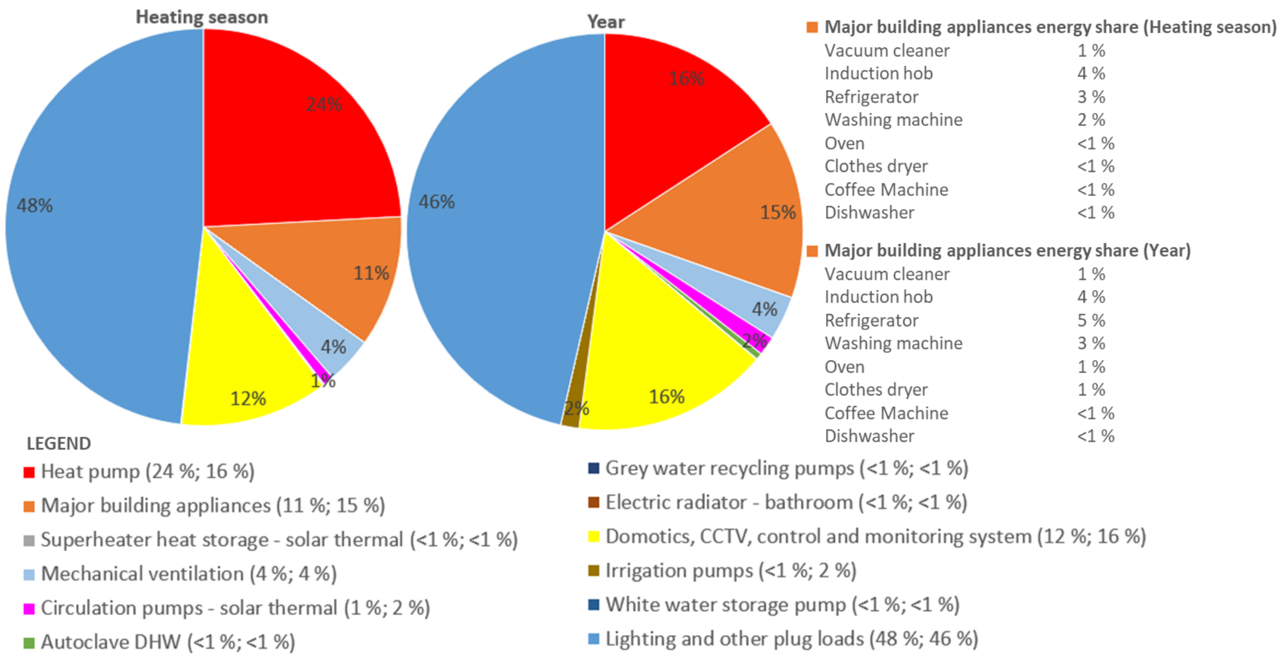


Fig. 12. Energy breakdown for the different energy services of the building during the heating season and during the whole monitored year. N.B. only energy shares higher than 1 % are showed in the pie charts.

4.4 Comfort analysis

A high performance building must guarantee adequate levels of thermal comfort to the occupants, while reducing the energy needs for heating and cooling [58], and the “nearly zero or very low amount of energy required should be covered to a very significant extent by energy from renewable sources, including energy from renewable sources produced on-site or nearby” [1]. Achieving this goal in the Mediterranean climate may be challenging in particular during summer, due to the high temperatures and potentially very high solar heat gains through opaque and transparent surfaces. The monitoring of the boundary conditions (i.e. outdoor weather conditions, occupation and control logic) and the environmental sensors installed inside the rooms of the house, have made possible a detailed thermal comfort analysis in parallel to the energy analysis.

The living room, the bedroom 1 (double bedroom) and the study room have been assessed from the point of view of thermal comfort, according to EN 15251 standard [59] that provides the “criteria for design and assessment of energy performance of buildings, addressing indoor air quality, thermal environment, lighting and acoustics”. The criteria for the design and assessment are defined according to four categories of comfort corresponding to the level of well-being to be achieved. In this case, the comfort analysis must be compliant to the comfort range defined for the category II, referred to a normal level of expectation of users for new buildings and renovations. Category III is on the other hand thought for existing buildings and everything beyond it should not be considered a comfort category.

The use of black globe sensors, together with air temperature probes, allowed the calculation of the mean radiant temperature and of the operative temperature in the three rooms, i.e. living room, bedroom 1 and study room. According to the EN 15251 standard [59], the acceptable operative temperature limits to perceive the environment as comfortable, depend on the type of system used in the building to provide comfort. These temperature limits are defined through comfort models (Fanger and adaptive) that quantitatively define thresholds for each category in relation to the control logics used. If thermal comfort is maintained through passive strategies (e.g. through natural ventilation only) the temperature limits are dictated by the adaptive model, whereas, if active strategies (e.g. mechanical heating and cooling) are used, indoor thermal comfort requirements and limits should be referred to the Fanger’s comfort model [15,60].

The adaptive comfort model follows a behavioural approach, assuming that people in daily life are not passive in relation to their environment, but tend to make themselves comfortable, given time and opportunity [7]. The building has been managed according to control logics that prefer passive cooling and passive ventilation strategies during summer and intermediate periods (the heat pump resulted active for cooling and DHW only 7 % of the time), while active strategies (with the activation of the heat pump) are chosen more constantly during the heating period. Therefore, the adaptive model better fits to the strategies used during the summer and intermediate period and the Fanger’s model to the strategies used during the heating season.

In Fig. 13 the fluctuation of indoor operative temperatures inside the living room (in dark grey), the bedroom 1 (in yellow) and the study room (in green) is drawn, contrasted to the three category ranges of the Fanger’s model during the heating season and of the adaptive model during the rest of the year. In the adaptive model, the temperature ranges fluctuate according to external temperature conditions and in the Fanger’s model the ranges are imposed by the EN 15251 and fixed throughout the reference period (Table 7). Fig. 13 shows that during the cooling and the intermediate period, excluding some exceptional cases, the comfort conditions are within the limits imposed by the reference category (Cat. II) of the adaptive model, for the investigated building, whereas during the heating period the comfort analysis according to the Fanger’s model, highlights some critical issues especially in the case of the study room (in green). The operative temperature of the study room does not respect the criteria imposed by the Fanger’s model especially near to the lower limits of the Cat. I and II. However, it is worth underlining that the set-point temperature defined by the occupats of the heating system was 19 °C, whereas the lower comfort limit for category II (according to Table A.3 of EN 15251) is 20 °C. So the building system worked to keep 19 °C degree in the building, and not 20 °C, that is why the comfort analysis in the winter time might be slightly misleading. On the other hand, occupants said they were comfortable with an indoor temperature of 19 °C, that is why they selected this value.

The study room show nevertheless some structural limits, affecting its operative temperature that is, indeed, strongly influenced by its limited floor dimensions (14.4 m^2), its location (north-west end of the building) and by the presence of two large windows. Moreover, this room is not regularly occupied and the daily internal heat gains are limited. The minimum temperatures recorded in this room (17 - 18 ° C) depend, therefore, also on these particular conditions. In particular, when the outdoor air temperature is very low and the room is not occupied, the heat losses through the envelope may affect the internal operative temperature considerably. However, the operative temperature recorded in this room does not respect, as well, the upper limit of the Fanger's model in some cases from November to the end of January. In presence of high solar radiation, the heat gains through the large glazing area, quickly affect the room operative temperature. Solar shading control is not, indeed, typically activated during the winter phase. Since the set-point temperature of the heating system (i.e. 19 °C) is lower than Cat. II's minimum threshold (i.e. 20 °C), and the temperature for the activation of ventilative cooling, during the heating period, is set to 28 °C, a value higher than Cat. II's maximum threshold (i.e. 25 °C), the comfort analysis during winter time, at least in the study room, is not particularly meaningful and definitely not representative of the average comfort conditions in the building. Due to the setting, the heating system experienced, thus, problems to control the temperature of a room characterised by very low internal heat gains and unpredictable solar gains.

The occupants of the building have confirmed this particular behaviour of the room that, nevertheless, does not play a relevant role in terms of thermal comfort of occupants, since it is rarely occupied. The other two monitored rooms of the house recorded, on the contrary, an optimal behaviour throughout the year, even with the unfavourable boundary conditions recorded during August 2017, when high outdoor air temperatures have been experienced even at night-time. Just during 16 % of the winter time (including night hours) the indoor temperature in the living room and bedroom 1 was below EN 15251 limit (i.e. 20 °C), and nevertheless higher than the heating system set point (i.e. 19 °C).

Table 7. Fanger's model - acceptable temperature ranges for heating season for residential building (Source: EN 15251).

Category	Fanger's model - acceptable temperature ranges for heating season for residential building (from Table A.3 of EN 15251)
I	21.0 – 25.0 °C
II	20.0 – 25.0 °C
III	18.0 – 25.0 °C

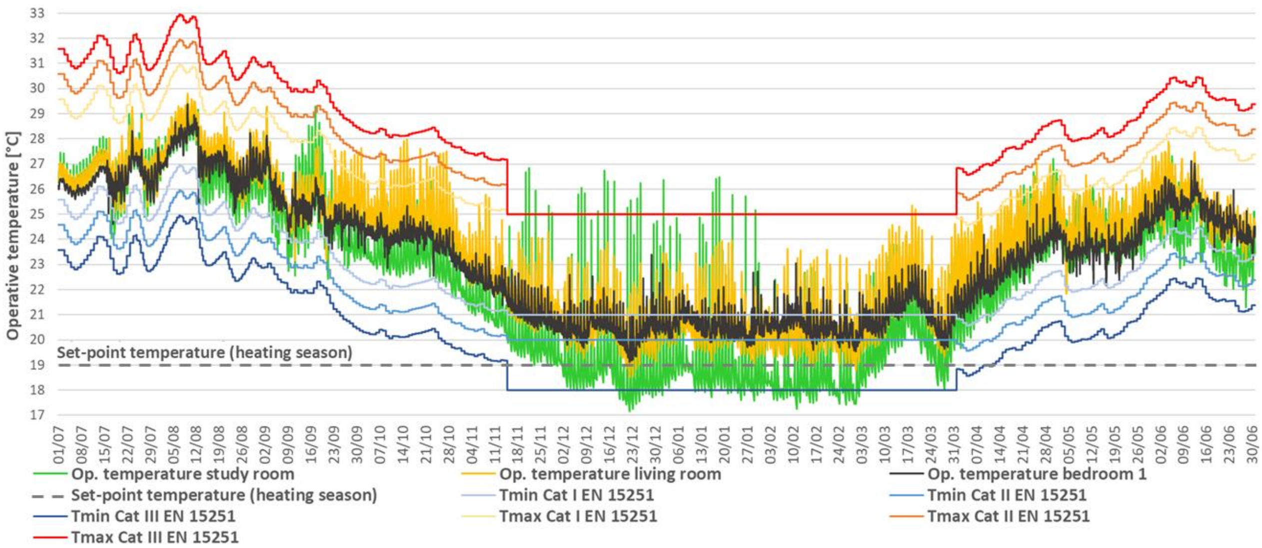


Fig. 13. Operative temperatures inside the living room, the bedroom 1 (double bedroom) and the study room contrasted with the three category ranges of the adaptive model.

A general overview of the internal operative temperature conditions recorded in the three representative environments of the building during the entire monitoring period are summarized in Fig. 14, that reports the percentage distribution of the indoor operative temperature inside the three studied rooms in relation to the comfort categories and their upper and lower limits during the whole monitoring year (*a*) and the heating season (*b*). The Cat. II includes all the operative temperature values that respect the temperature limits imposed by the adaptive and the Fanger's model, the term "upper end" indicates the temperature values included in Cat. III and above it (all values beyond the Cat. II) that are higher than the limits imposed by the Cat. II for the temperature. Vice versa, the term "lower end" indicates the temperature values included in Cat. III and below it (all values beyond the Cat. II) that are lower than the limits imposed by the Cat. II for the temperature.

During the year and the heating season the discomfort conditions are mainly related to an uncomplete fulfilment of the lower operative temperature limits. Considering the whole year, Cat. II includes 86 % of the operative temperature recorded in the three analysed rooms. The remaining 14 % of the operative temperature values fall beyond Cat. II and, respectively, 12.4 % in Cat. III and 1.6 % beyond Cat. III. Focusing on the recorded operative temperature values during the heating season (Fig. 14b) the situation changes: 63.3 % of the values fall within the Cat. II and the remaining values are included respectively in Cat. III (32.2 %) and below Cat. III (4.3 %).

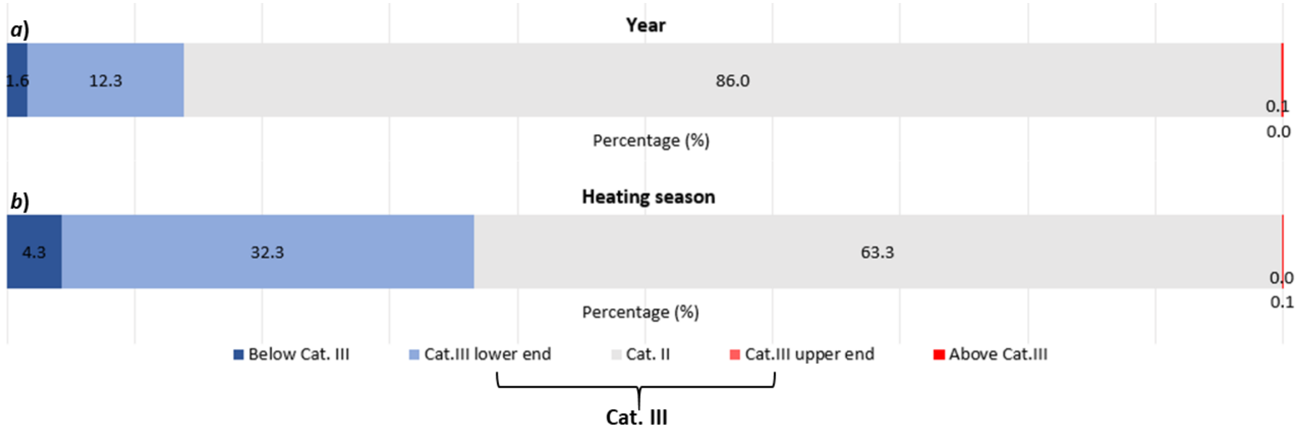


Fig. 14. Percentage distribution of the operative temperature of the living room, bedroom 1 and study room in relation to the comfort categories and their upper and lower limits during the whole monitoring year (a) and the heating season (b).

Since we reported that the comfort conditions recorded within the study room, and included in the previous analysis, are not representative of the average comfort conditions in the most occupied rooms of the building, the same analysis has been carried out considering only the living room and the bedroom 1. Fig. 15 shows the percentage distribution of the indoor operative temperature inside the living room and the bedroom 1 in relation to the comfort categories and their upper and lower limits during the whole monitoring year (*a*) and the heating season (*b*). The results, compared to the previous ones, improve both in case of yearly analysis and heating season analysis. Considering the whole year, Cat. II includes 93.8 % of operative temperature values, only 6.2 % of the temperature values fall beyond the Cat. II and are all included in the Cat. III; in this case, there are no temperature values that exceed the limits of Cat. III. Focusing on the heating season, no operative temperature values exceed the limits of Cat. III and the percentage of temperature values included in Cat. II increases (83.8 % values within the reference Cat. II). The remaining temperature values (16.1 %) are included in Cat. III and exceed the lower temperature limit of Cat. II.

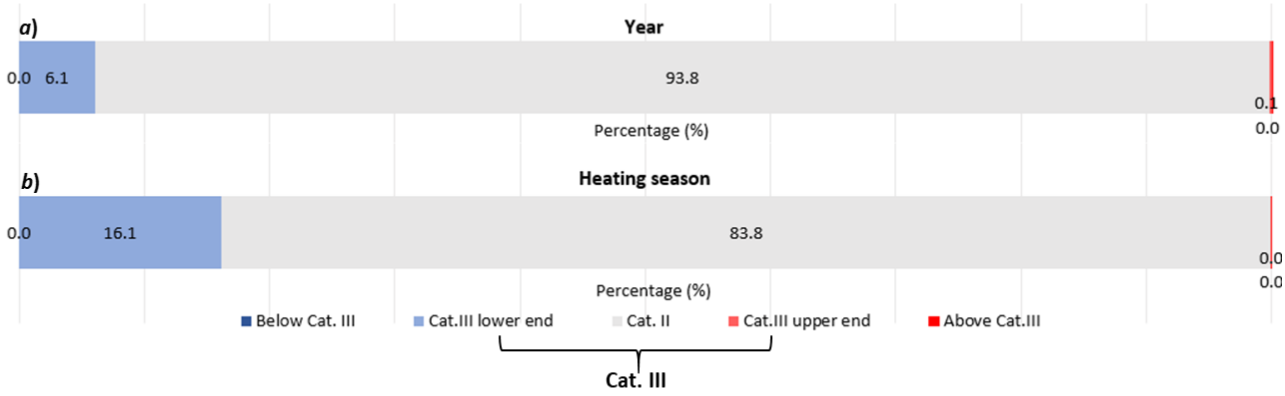


Fig. 15. Percentage distribution of the operative temperature of the living room and bedroom 1 in relation to the comfort categories and their upper and lower limits during the whole monitoring year (a) and the heating season (b).

A final additional analysis was performed (Fig. 16) using as a lower comfort limit of the Cat. II, the one proposed by occupants (i.e. 19 °C, the set point temperature) for the living room and the bedroom 1 only. This analysis showed that almost no discomfort hour has been registered in the building, also during winter, and that the building systems properly managed to keep the desired temperature.

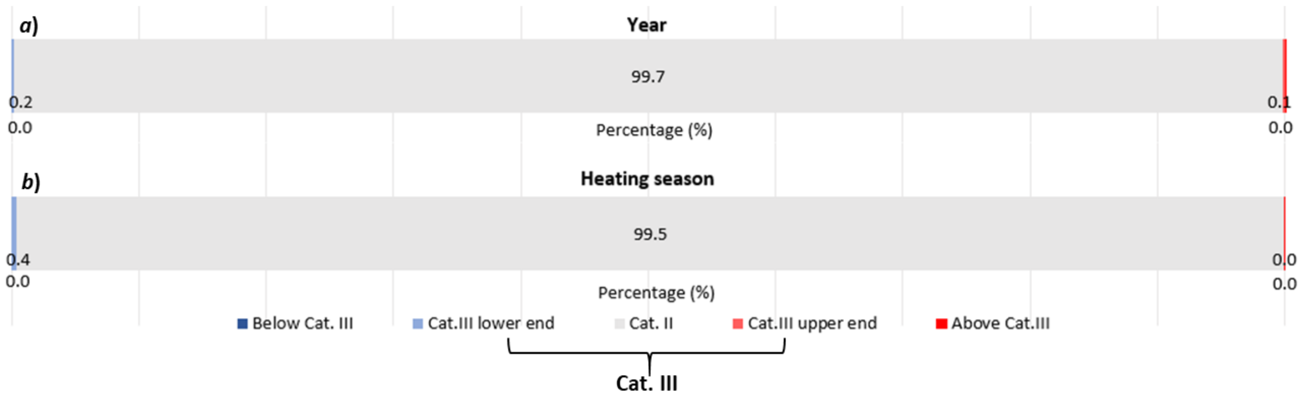


Fig. 16. Percentage distribution of the operative temperature of the living room and bedroom 1 in relation to the comfort categories and their upper and lower limits (lower limit of Cat. II equal to 19 °C) during the whole monitoring year (a) and the heating season (b).

5. Major results summary and discussion

The analysis of energy and comfort performance, conducted on yearly basis, on the Passivhaus located in the municipality of Mascalucia, has highlighted an optimal behaviour of the building, even in the case of unfavourable external climatic conditions. The set control logics have favoured passive and low-energy solutions during cooling and intermediate period and active solutions during the heating season. When the passive solutions have not been able to maintain comfort conditions, active strategies have been activated, also on the basis of the feedback of the occupants.

The building can be defined as a prosumer, since the yearly production of the electrical energy by PV system substantially compensates and overcomes the total yearly energy use. Only during the central winter months, the energy balance of the building is slightly negative, since strongly influenced by the more regular and constant use of the heat pump for heating and for the production of DHW.

The primary energy demand for all domestic electric services of the building can be considered in line with the limits imposed by the requirements of the Passivhaus when the building was certified (i.e. 2013). The total primary energy use (144.5 kWh/m^2_{net}/year), indeed, although being slightly higher than the limit value of 120 kWh/m^2/year, has been calculated including non-domestic and not individually monitored services as well as non-standardized operational and boundary conditions such as those normally used in the Passivhaus certification procedure. For example, the calculation of the HDD highlighted unfavourable weather conditions compared to the standard ones.

The ratio between daily energy produced by PV and the total daily energy use has been analysed, its value is higher in the summer months than in winter ones in relation to the different boundary and operational conditions. Considering the whole year, 63 % of the values of this ratio is greater than 1, i.e. the production of PV energy is greater than the total energy use. More accurate analysis on this topic might lead to further consideration on the possibilities and limitations of installing battery storage systems.

The detailed analysis of the main energy uses of the building has shown that the heat pump and the home automation system account both for 16 % of the total energy use of the whole year. However, while the heat pump energy use varies depending on the season and users' preference, the energy use for the home automation system is constant throughout the year. It is worth mentioning that the home automation includes the anti-theft system also (i.e. an energy intensive CCTV). Finally, the analysis showed that about 72 % of the total energy use is depending on occupants' behaviour and preferences. The current monitoring set-up does not allow distinguishing between lighting and plug loads, this is a major limitation that must be challenged and overcome to provide a more accurate energy breakdown, and further insight on occupant behaviour.

Finally, the monitoring outcomes show that the building is able to maintain a quite stable thermal comfort despite particularly difficult climatic conditions registered during the summer and the winter period. The comfort analysis has been conducted in three representative rooms of the house where an advanced comfort instrumentation has been installed. The analysis has been carried out according to the Fanger's comfort model for the heating season (15/11 – 31/03) and the adaptive comfort model for the rest of the year. The limits imposed by the adaptive model for the Cat. II, have been fulfilled throughout the entire considered period, while those imposed by the more restrictive Fanger's model have highlighted critical thermal comfort conditions in one of the three analysed room during the winter season. This critical behaviour is due to the unfavourable climatic conditions recorded during the heating season and to the fact that the room, due to its position inside the building and its geometric characteristics, is subjected to high heat losses in case of very low temperatures and to rapid temperature increases in case of high solar radiation. The room is, however, sporadically occupied and the users did not report particular discomfort sensation. A further analysis considering the heating system set point (19 °C), that was lower than the EN15251 lower limit (20 °C) for Cat. II, reports almost no discomfort hour in the living room and the main bedroom. The results of the comfort analysis according to adaptive model, substantially reflect the perception and the sensation declared by the occupants of the building during the monitoring period.

New thermal comfort models and metrics are necessary for high performance buildings and different final uses, further than offices (e.g. residential, kindergarten, malls, etc.). Currently both the designer and the professional in charge of performance assessment, are dealing with tools developed on the basis of databases and hypothesis substantially different from the specific object of investigation (i.e. the building and its occupants), and this might bring to inaccurate conclusions that might either lead to a reduced energy or comfort performance, depending on the deterministic choice of the operator.

The energy performance of the building has been compared to the few data available in the literature, for high performance residential buildings, in similar climatic conditions (i.e. Csa or Cfa under Köppen climate classification). Table 8 shows that operational performance data with a detailed breakdown is still very limited in literature; however, according to heating and DHW, the Passivhaus in Mascalucia reports performance in line with similar buildings, whereas the PV production is substantially higher, due to a wider panel surface.

Table 8. Energy use and energy production of high performance residential buildings in climate of Southern Europe (Csa and Cfa – under the Köppen climate classification)

		Energy production [kWh/m²/year]	Energy use [kWh/m²/year]						
Case study	Köppen classif.	PV	Total energy use	Heating, cooling, DHW	Major appliances	Mech. ventilation	Domotics, CCTV, control and monitoring system	Lighting and other plug loads	Other (pumps, etc.)
Mascalucia, Sicily	Csa	76.02	59.71	7.27 (heating + DHW)	8.84	2.18	9.67	27.72	1.70

				2.33 (cooling + DHW)					
Trino, Piedmont [17]	Cfa	17.32	-	25.81 (heating) 2.05 (DHW)	-	-	-	14.88 (lighting)	-
Bucharest [19]	Cfa	11.12	-	13.12 (heating)	-	-	-	-	-
Piedmont (ten buildings) [20]	Cfa	-	-	9.00 ÷ 15.00 (heating, cooling, DHW, electric appliances)		-	-	-	-
Rosora [27]	Csa/Cfa	53.80	91.00	27.00 (heating)	-	-	-	-	-

6. Conclusions

Operational data on building performance and occupant behaviour, gathered from monitoring campaigns, post-occupancy evaluations and on-going commissioning, are fundamental to characterise the building stock to drive energy policies, to design smart grids capable to manage highly dynamic loads, e.g. as consequence of time varying renewable energy input into the grid, and to develop flexibility services such as demand-side response programs, able to shift loads without requiring major investments for new power plants.

Unfortunately, high frequency data on building performance are not easily available in the literature, especially for high-performance buildings, such as nZEB or passive houses, that are, nevertheless, substantially promoted by directives, guidelines and laws on energy performance.

In this paper we reported the results form a yearly energy and comfort experimental campaign, on a Passivhaus certified building, located in the Mediterranean climate. The building, as a living lab, is equipped with advanced monitoring instrumentation, able to provide data with high frequency and detail. The analysis of data concludes that the building reaches a yearly positive energy balance; however, to better use on-site generated energy, reducing the use of the national grid as an off-site storage, local storage systems would be required. The use of these systems might be affected by substantial seasonal dynamics, mostly depending on the use of space heating and cooling systems, and by occupant behaviour. In particular, the detailed energy breakdown of the building showed that about 72 % of the energy use of the building is affected by occupants' choices and behaviour. The share of heating and cooling systems and the related thermal comfort services is about 16 %, whereas the share of electrical appliances, including the major appliances used for cooking and washing, is about 56 %.

Even if we do not know yet if the recorded values refer to austere, average or wasteful users (a larger database is required for this identification), these data should be carefully observed by designers and policy makers, because they say that high performance buildings may really operate the way they are designed to, only if users adopt a well informed and careful behaviour. Where is the optimal balance between automatic control and manual operation is a fundamental object of investigation for the future, evaluating it both in terms of energy use and the related energy service provided (thermal comfort, visual comfort, etc.).

The data available from the monitoring campaign reported in this paper already showed, for the living lab, that if on the one hand the installed automation and monitoring system provides effective control of all the services of the building (heating, cooling, lighting, etc.), improving at the same time comfort and energy efficiency, on the other hand it has a not negligible impact on the overall building energy performance. However, it is worth mentioning that in the analysed building the monitoring and automation system also includes the energy use for the anti-theft protection system and then an energy intensive Closed Circuit TV, thus the available data are not solely related to basic comfort services.

Future developments of the monitoring activity will include the analysis of load matching and grid interaction to evaluate the possibility of implementation of a battery energy storage system. With this equipment, the building could considerably increase the self-consumption of energy produced on site by PV, minimizing the grid interaction and therefore the operational energy cost and the environmental impact; it might also help increasing grid flexibility on the demand side. Other detailed studies might include the performance analysis and modelling of the EAHE, and other building services systems.

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